A Large LAr TPC Detector for the NuMI off-axis beam

Alberto Marchionni, Fermilab

- **Next challenges in neutrino physics call for larger and specialized detectors**
  - beam optimization is a key element of the experiment
  - a large step in the size of the detector is required
    - … not every detector technology of the past has large scaling capability
- **Liquid Argon TPC's**
  - the ICARUS experience
  - concepts for a large LAr TPC for NuMI
- **R&D plan towards large LAr TPCs**
- **Conclusions**

The present picture of neutrino oscillations

For 3 ν's:

Atm. ν Reactor, accel. solar

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Where $c_{ij}=\cos_{\theta ij}$, $s_{ij}=\sin\theta_{ij}$,
δ = CP viol. phase

Our supposed knowledge

$\Delta m_{12}^2 = \Delta m^2_{sol} = 8.0^{+0.6}_{-0.4} \times 10^{-5}$ eV^2, $\tan^2\theta_{12} = 0.45^{+0.09}_{-0.07}$

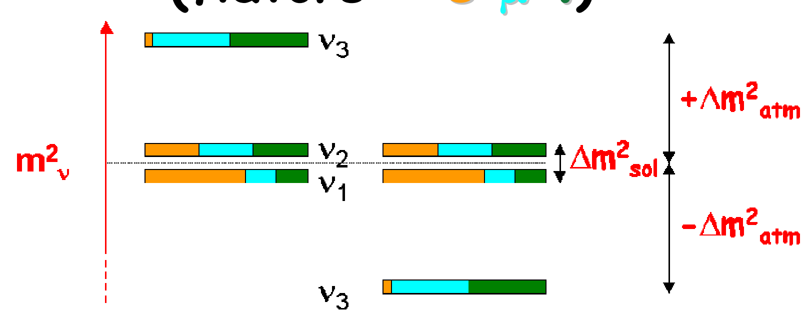
$\Delta m_{23}^2 = \Delta m^2_{atm} \simeq 1.5\text{-}3.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.92$

$\sin^2 2\theta_{13} < 0.14$ @ $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

Our known ignorance

$\sin^2 2\theta_{13}$, sign(Δm_{23}^2), δ
LSND signal (???)

(flavors = e μ τ)



New Initiatives: neutrinos

- Understanding the Neutrino matrix:
  - What is $sin^2 2\theta_{13}$
  - What is the Mass Hierarchy
  - What is the CP violation parameter δ
- Fermilab is in the best position to make vital contributions to answer these questions

P. Oddone September 12, 2005

$\nu_\mu \to \nu_e$ appearance at the atmospheric mass scale

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2} G_F n_e;$$

$$B_\pm = |A \pm \Delta_{13}|;$$

$$J = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$P_1 = \sin^2\theta_{23} \sin^2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

Oscillation at the 'atmospheric' frequency

$$P_2 = \cos^2\theta_{23} \sin^2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

Oscillation at the 'solar' frequency

$$P_3 = J\cos\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \cos\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \sin\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

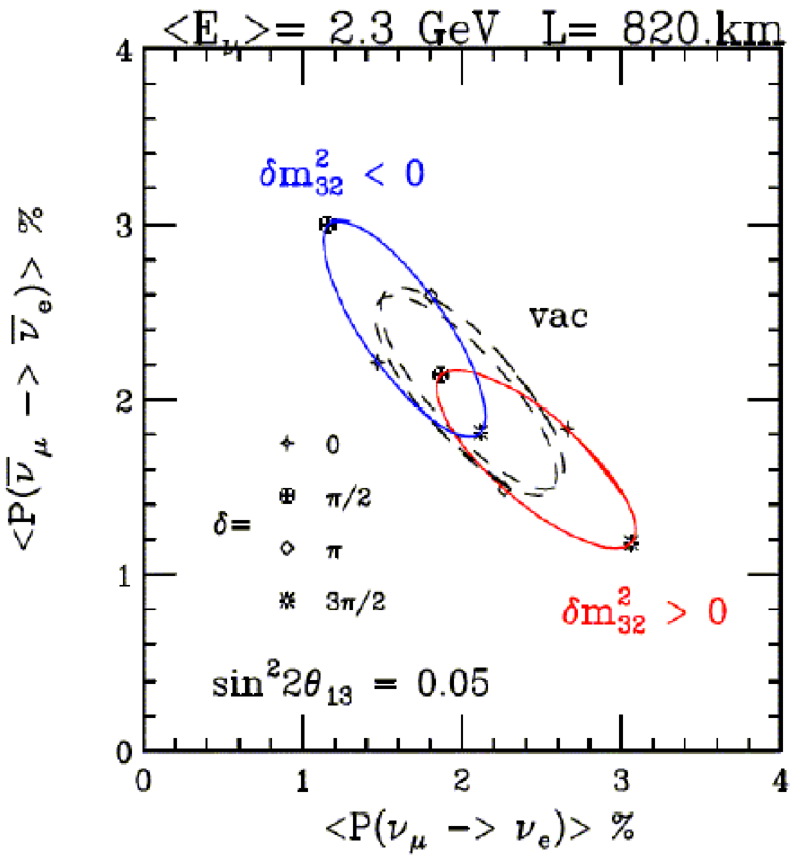
Interference of these two amplitudes ➔ CP violation

$$P = f(\sin^2 2\theta_{13}, \delta, \mathrm{sgn}(\Delta m_{13}^2), \Delta m_{12}^2, \Delta m_{13}^2, \sin^2 2\theta_{12}, \sin^2 2\theta_{23}, L, E)$$

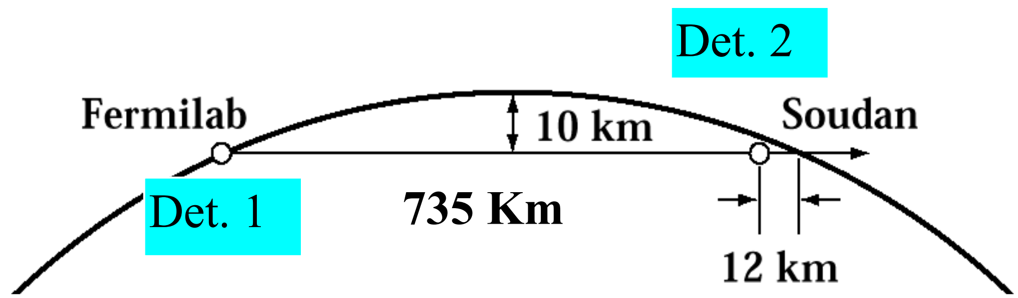
3 unknowns, but we have a choice of L, E, neutrino/antineutrino running

What it takes to do these measurements

- **We want to be sensitive to oscillation probabilities down to few$\times 10^{-3}$**
- Experiments, at least in a first phase, will be statistics limited
- **3 unknown (θ_{13}, δ, sign(Δ_{23}^2))**
- **we need several independent measurements to learn about underlying physics parameters**

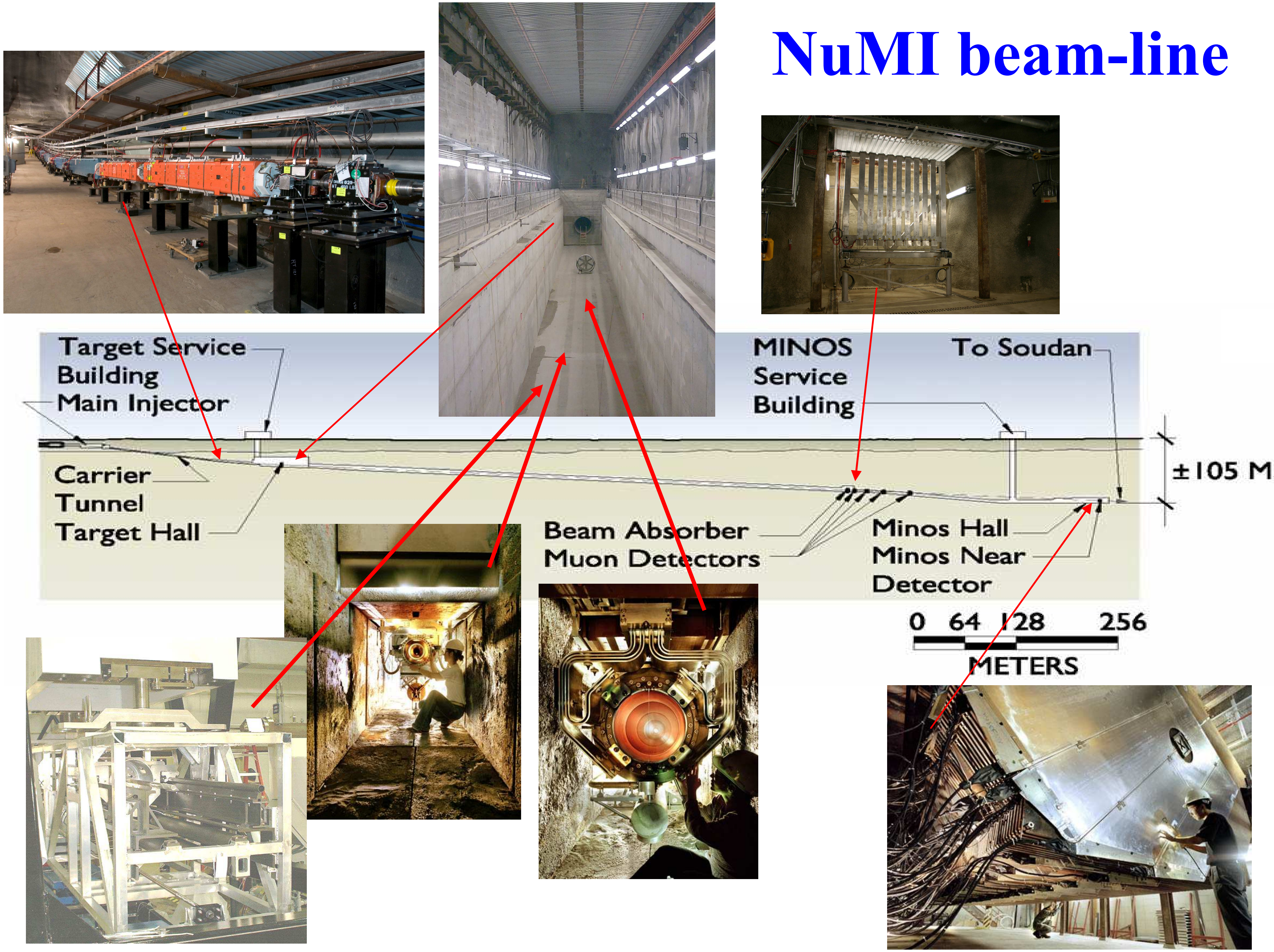


NuMI: ν's at the Main Injector

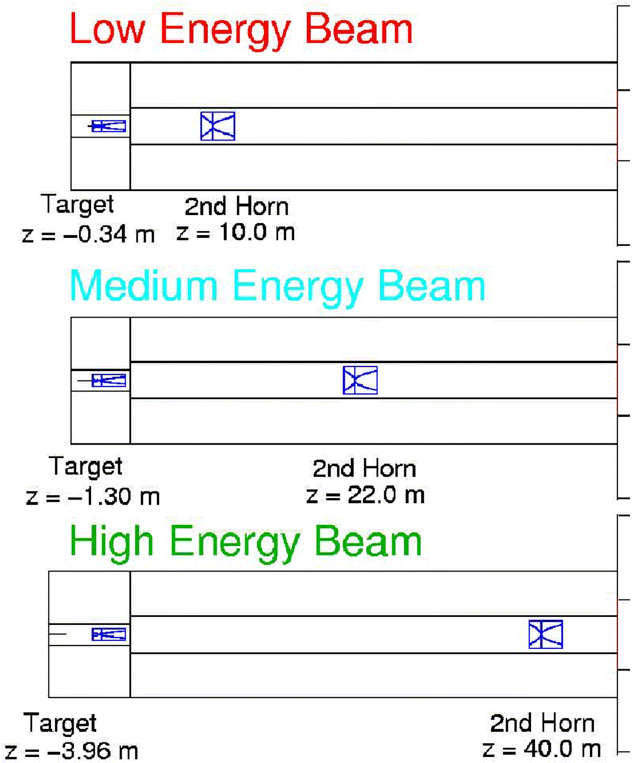


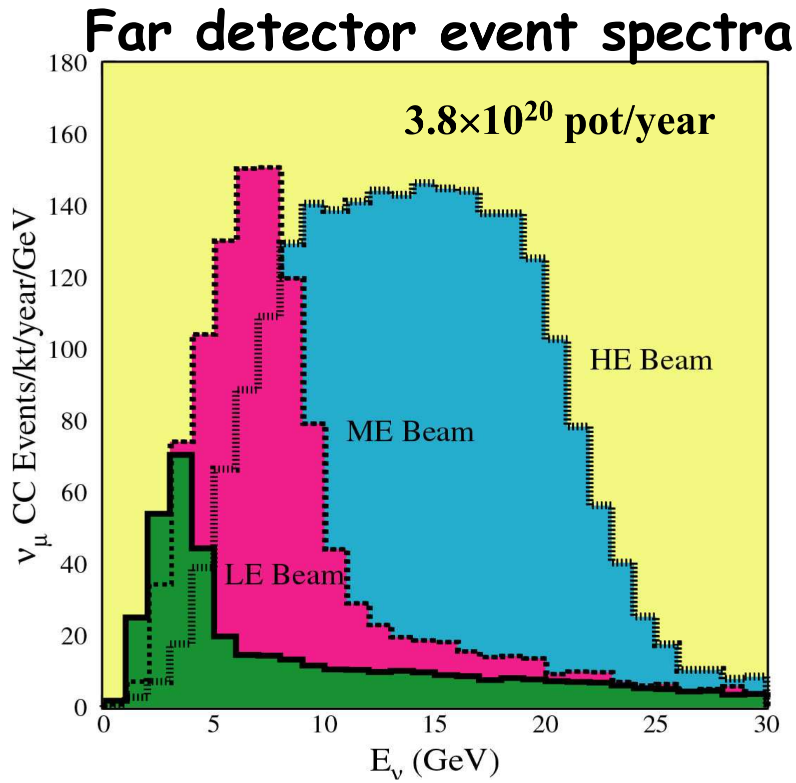
- **a neutrino beam from Fermilab to northern Minnesota**
  - over 735 km to Soudan mine (MINOS experiment)
  - **a large near hall at ~ 1 km from the target**
  - MINOS near detector, MINERνA, PEANUT (exposure of OPERA bricks)
- **a high power neutrino beam**
  - 120 GeV protons from Main Injector
  - **facility designed for up to 0.4 MW (4×10^{13} ppp every 1.9 s)**

NuMI beam-line



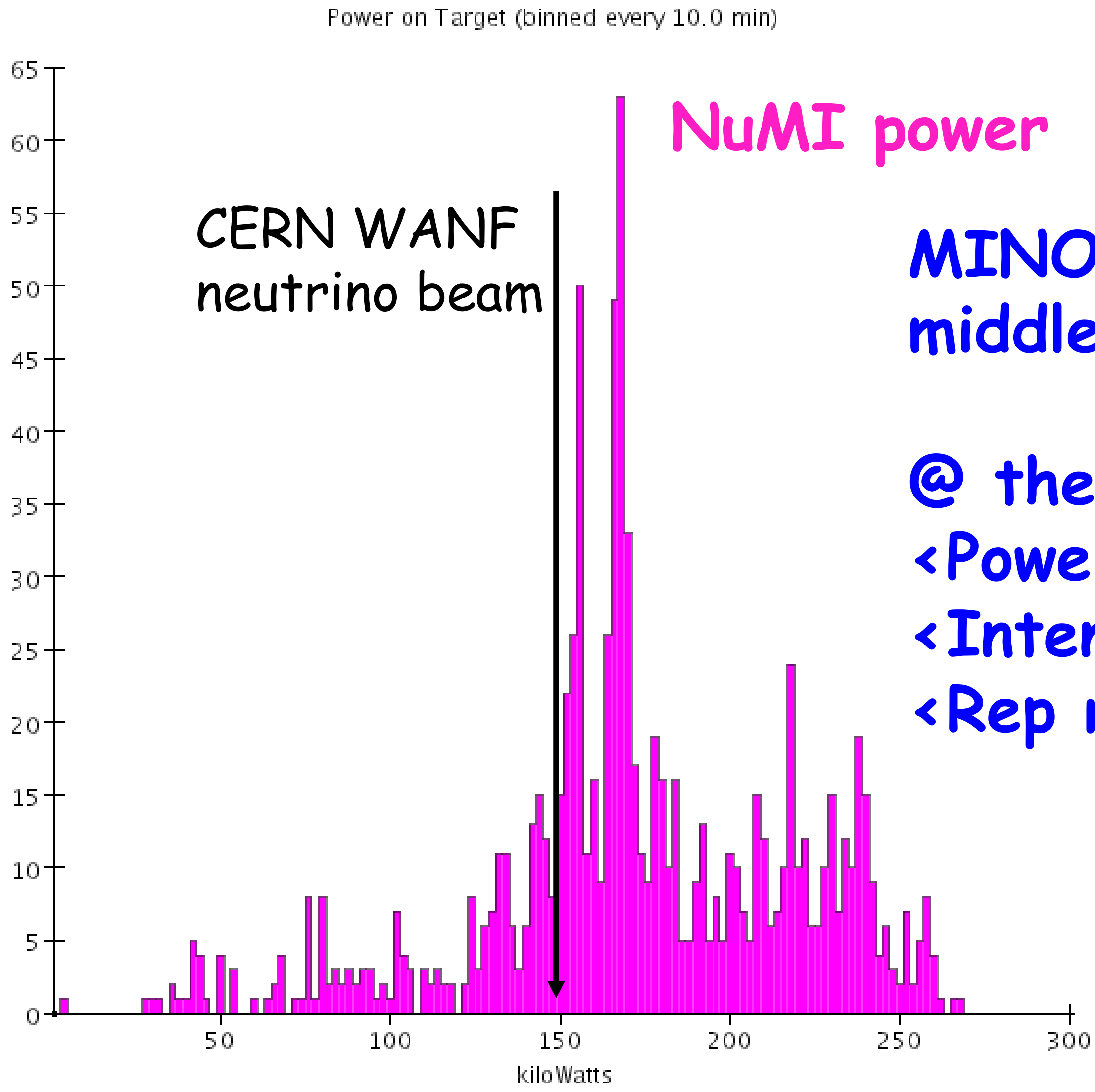
A flexible target and horn system





- Fully optimized spectra for each energy are obtained by moving the target and the 2nd horn
- in LE configuration, 2/3 of the target length is positioned inside the 1st horn
- With a parabolic shaped horn inner conductor, the horn behaves like a lens (p_t kick proportional to the distance from the axis), with a focal length proportional to the momentum

NuMI performance



MINOS data taking started middle of March '05

@ the end of September

<Power>= 172 kW

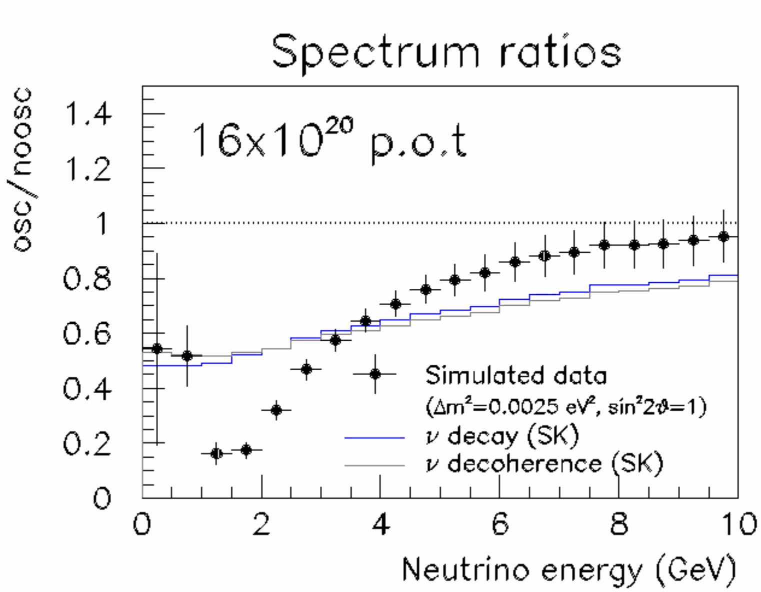
<Intensity> = 2.4×10^{13} ppp

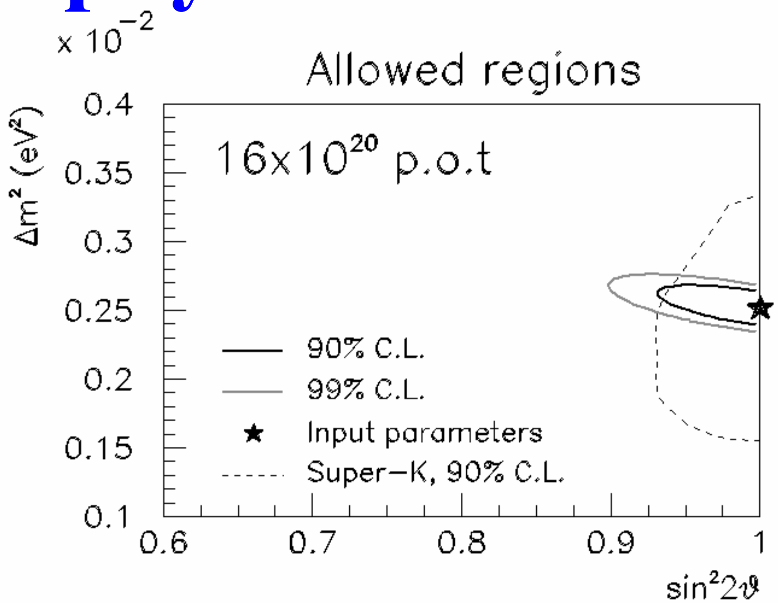
<Rep rate> = 2.45 s

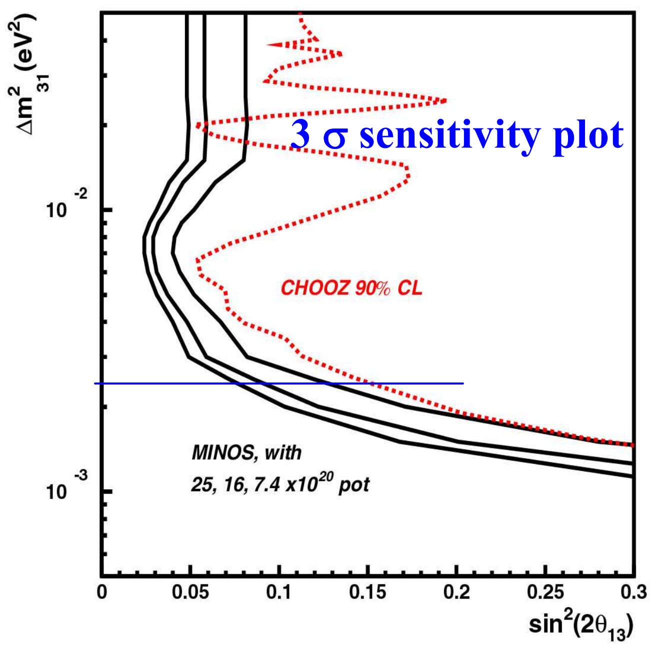
MINOS Far Detector

- 2 sections, each 15m long
- 8m Octagonal Tracking Calorimeter
  - 486 layers of 2.54cm Fe
  - 4cm wide solid scintillator strips with WLS fiber readout
  - longitudinal granularity 1.5 X_0
  - Magnet coil provides $\langle B \rangle \approx 1.3T$
- **5.4kt total mass**
- Fully loaded cost ~$6 M/kton

MINOS physics reach



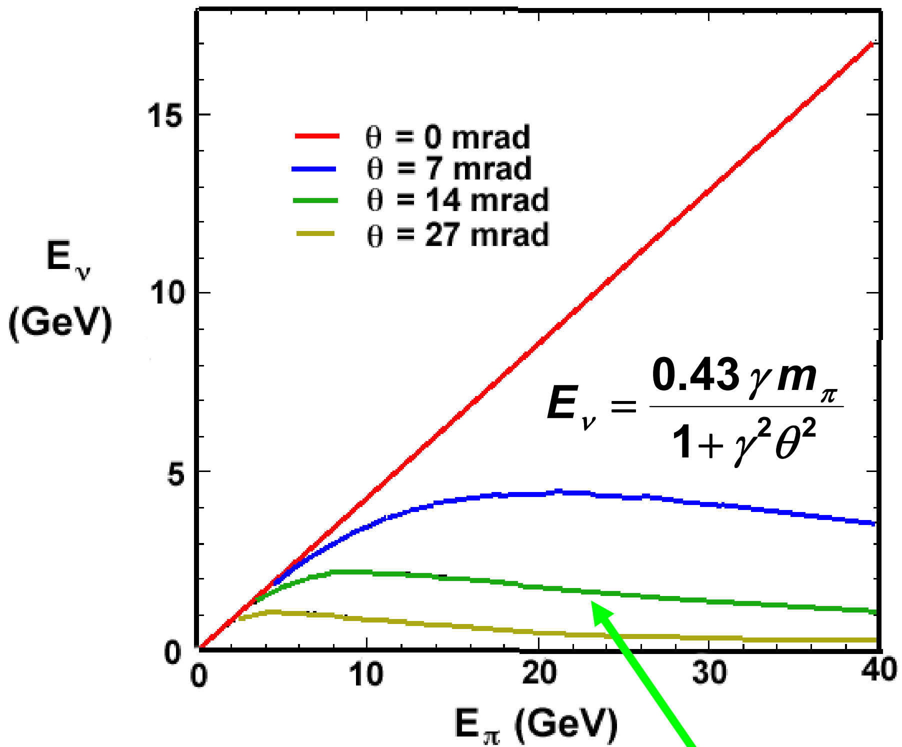




In ~ 5 years

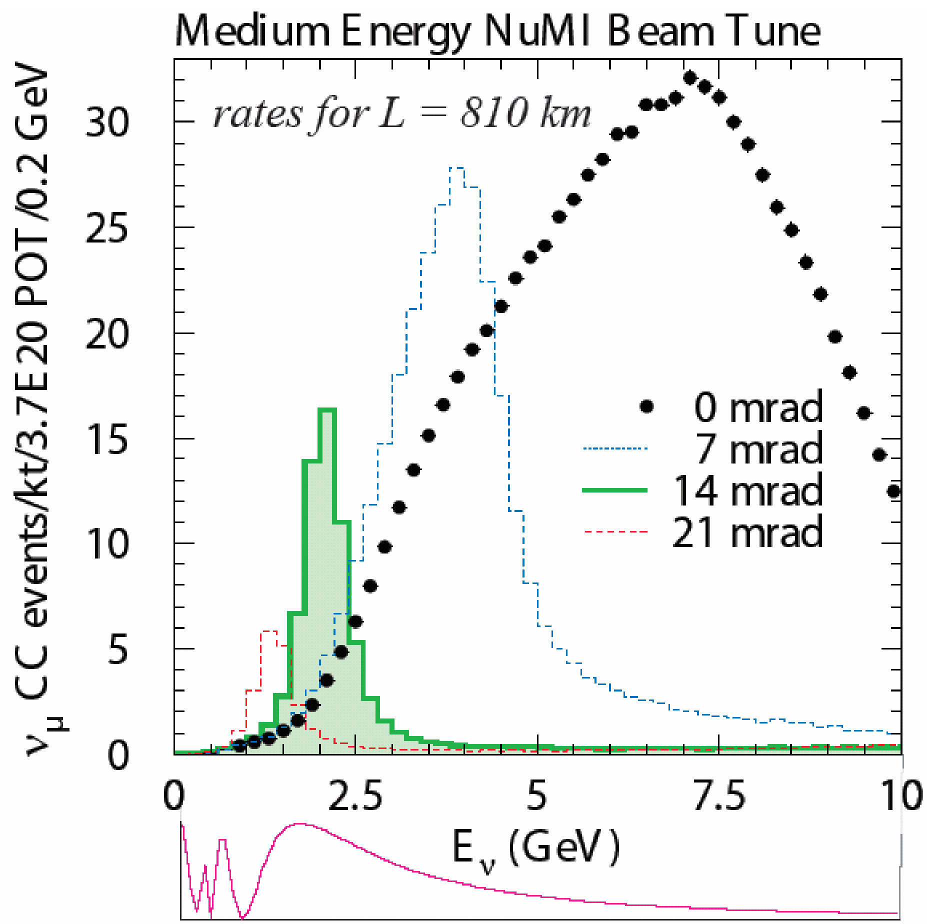
- **10% measurement of atmospheric Δm^2, good sensitivity for unconventional explanations**
- **3 σ sensitivity for non-zero θ_{13} if within a factor 2 of the CHOOZ limit**

NuMI as an Off-Axis beam



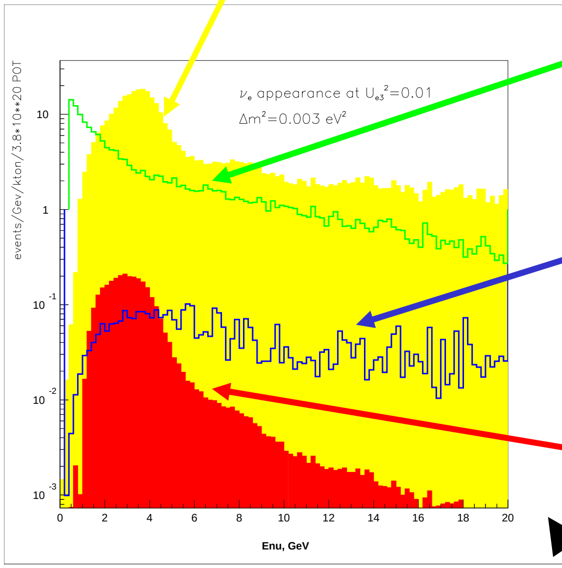
For a given θ≠0, a large range of pion energies contributes to a small range of neutrino energies

Off-axis beam from ME configuration



How to improve ν_e signal/background: choice of the beam

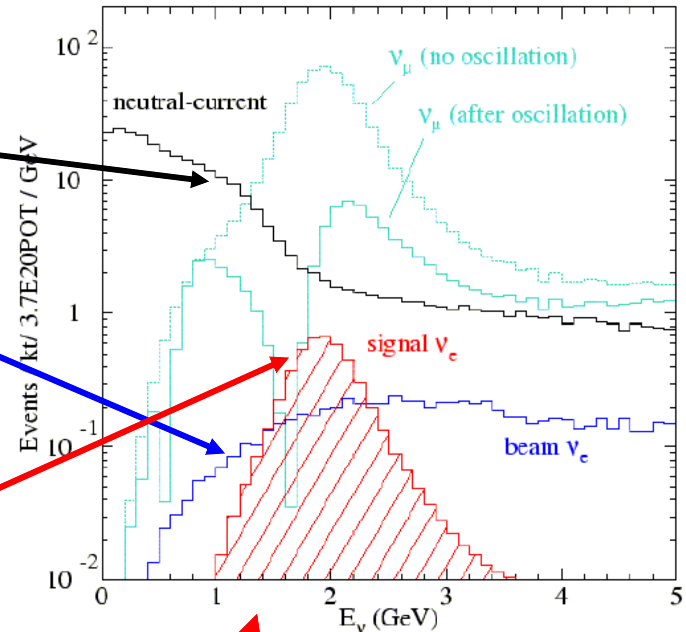
ν_μ spectrum



NC (visible energy), no rejection

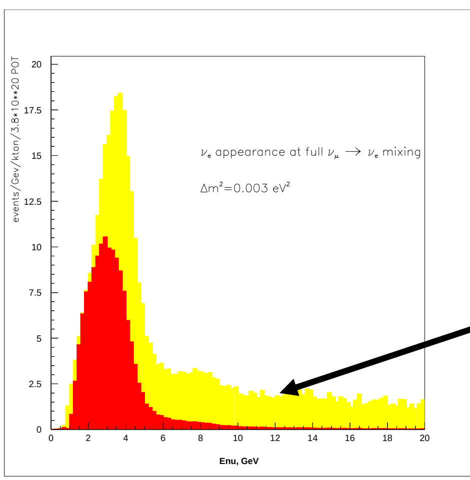
ν_e background

ν_e ($|U_{e3}|^2$ = 0.01)



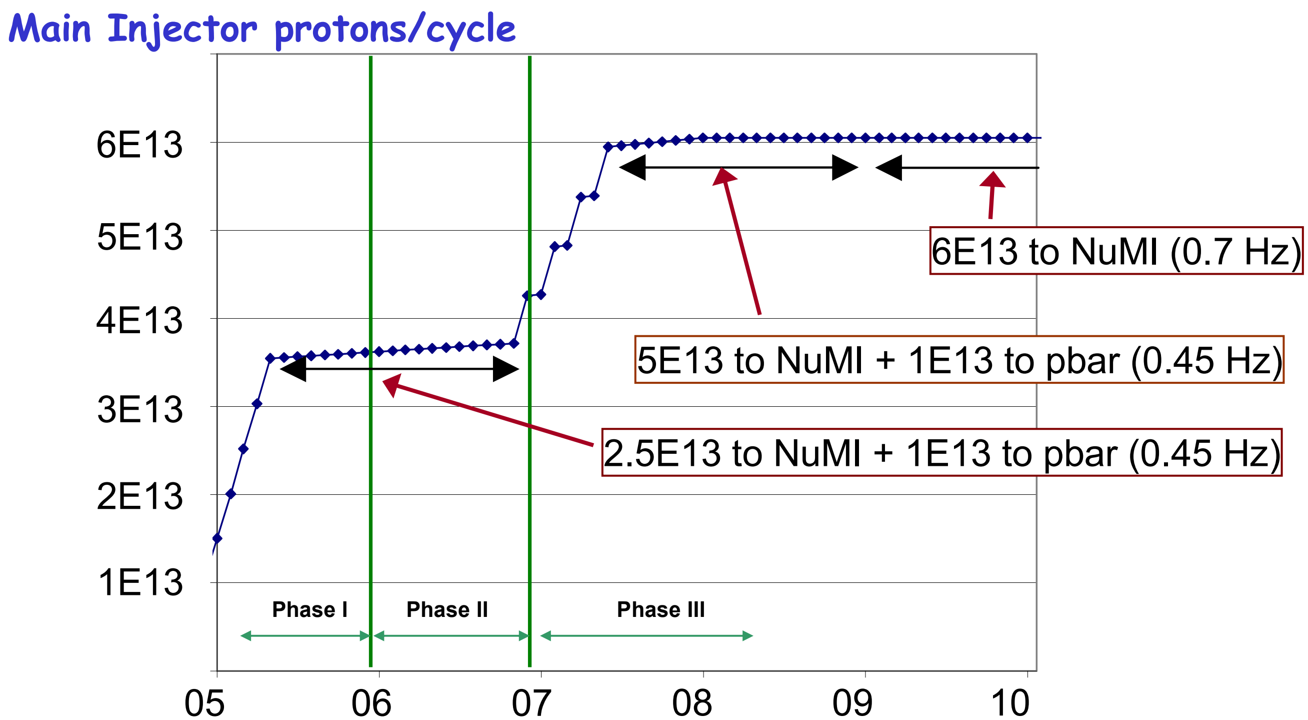
NuMI low energy beam

NuMI off-axis beam



These neutrinos contribute to background, but not to the signal

Beam power upgrades



NuMI flux to MINOS ~ 2 x 10^{20} protons/year (now)

'Proton Plan' (remove existing limitations) gives NuMI

~ 4 x 10^{20} protons/year before collider turn-off in 2009

~ 6 x 10^{20} protons/year after collider turn-off in 2009

Proton Driver (new Linac) ~ 25 x 10^{20} - whenever PD exists

A Detector for NuMI off-axis

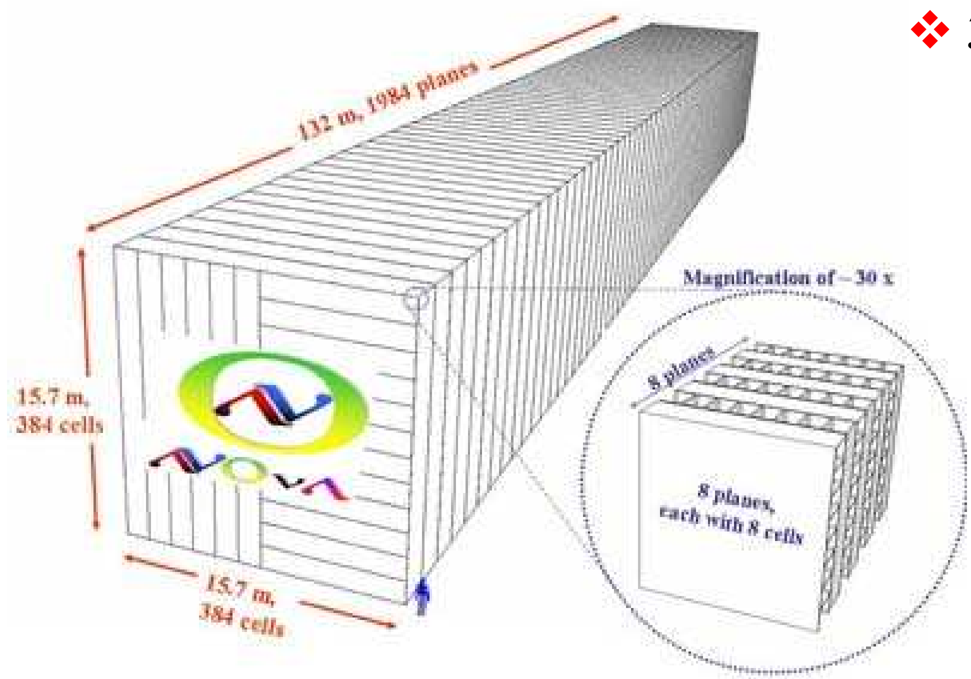
- **Physics requirements**
  - optimized for the neutrino energy range of 1 to 3 GeV
  - detector on surface, must be able to handle raw rate and background from cosmic rays
  - very large mass (10's kton range)
  - identify with high efficiency ν_e charged interactions
  - good energy resolution to reject ν_e's from background sources
    - ν_e background has a broader energy spectrum than the potential signal
  - provide adequate rejection against ν_μ NC and CC backgrounds
    - e/π^0 separation
      - fine longitudinal segmentation, much smaller than X_0
      - fine transverse segmentation, finer than the typical spatial separation of the 2 γ's from π^0 decay
    - e/μ,h separation

Neutrino Initiative: NOvA

- In addition to Beam power: detector mass and detector sensitivity: NOvA is 30 ktons, totally active
- NOvA is the only experiment sensitive to matter effects (hence the mass hierarchy).
  - We want to start a long term R&D program towards massive totally active liquid Argon detectors for extensions of NOvA.
  - Improvement is proportional to (Beam power) x (detector mass) x (detector sensitivity)

P. Oddone September 12, 2005

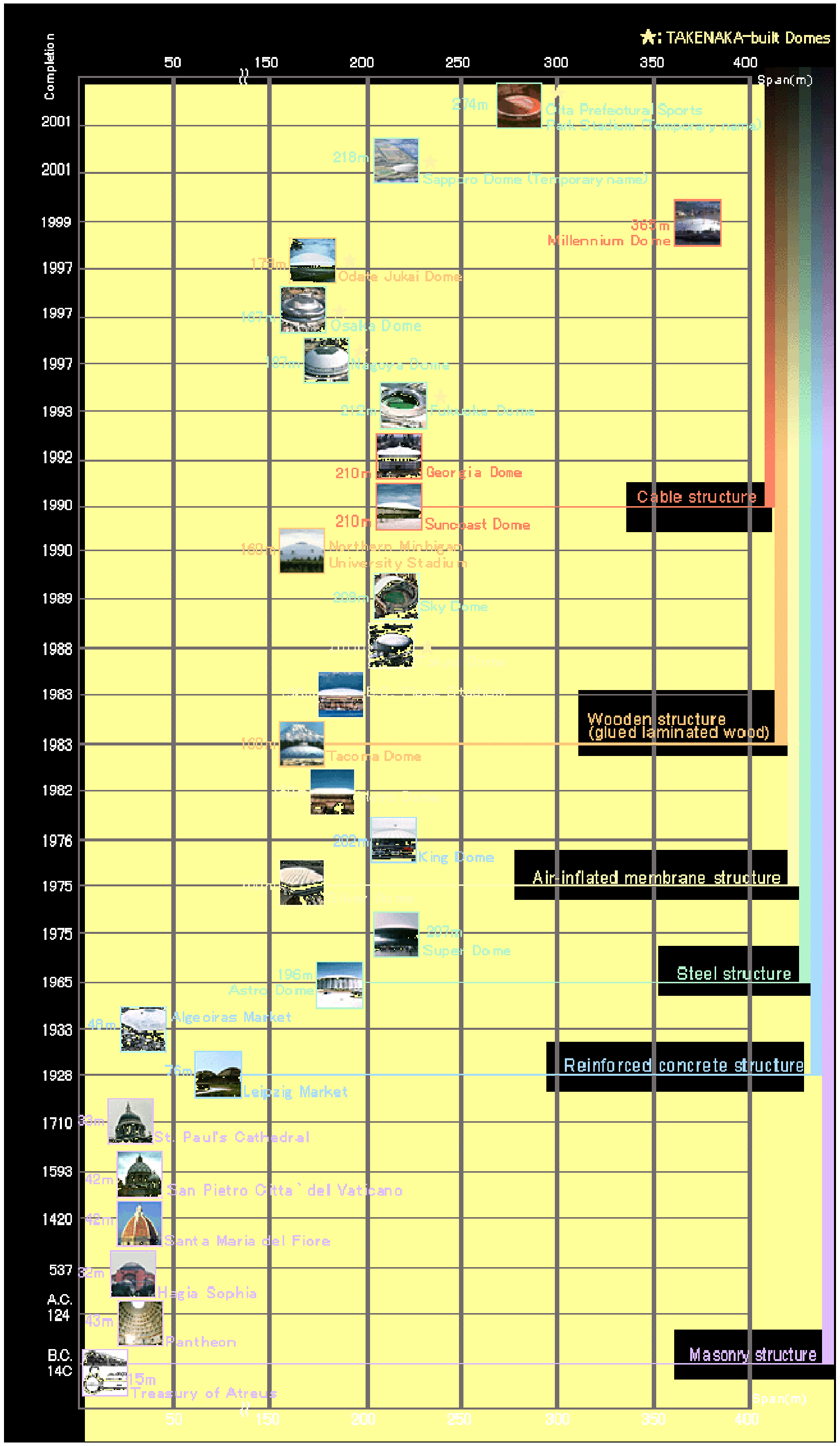
NoVA



- 30 kton tracking calorimeter
  - alternating horizontal and vertical cells of liquid scintillator contained in PVC
  - 80% active material
  - cell size: 15.7 m long, 3.87 cm wide, 6.0 cm along beam direction
  - 0.8 mm ∅ looped WLS fibers in each cell for light collection
  - the 2 ends of a looped fiber connected to 1 pixel of an APD

- Longitudinal granularity 0.15 X_0
- Efficiency for ~ 2 GeV ν_e events ~ 24%
- Background fraction for ν_μ NC ~ 2×10^{-3}
- Background fraction for ν_μ CC ~ 4×10^{-4}

Scaling violations



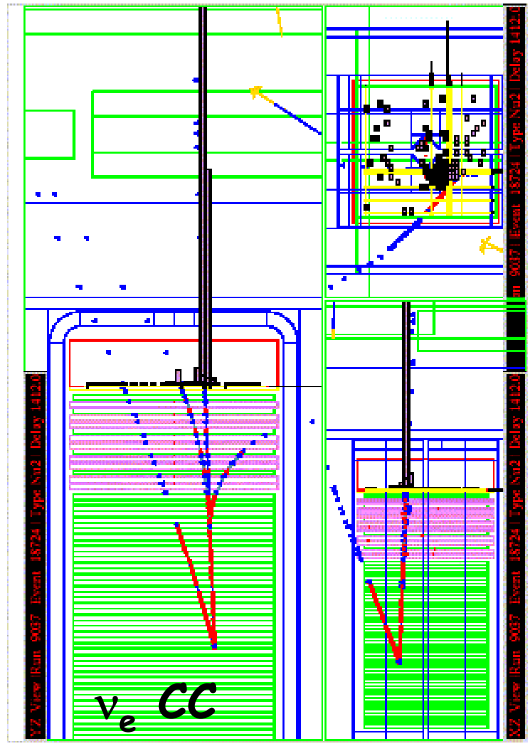
Florence Dome, span 42 m, masonry structure

Oita sports park "Big Eye" dome, span 274 m, steel structure

Millennium Dome, Greenwich, London, span 365 m, cable structure

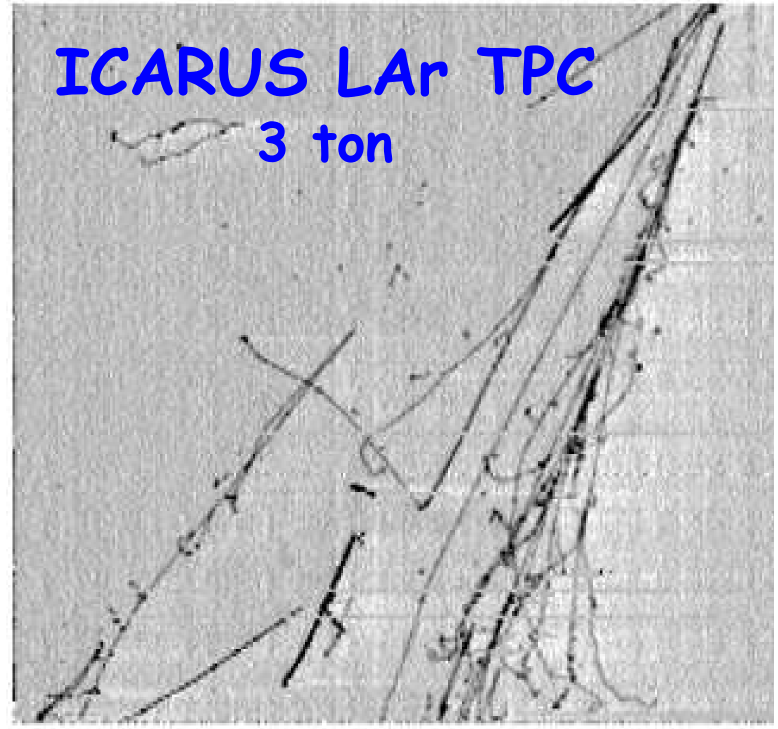
Bubble ∅ (mm)	3
Density (g/cm^3)	1.5
X_0 (cm)	11.0
λ_T (cm)	49.5
dE/dx (MeV/cm)	2.3

NOMAD



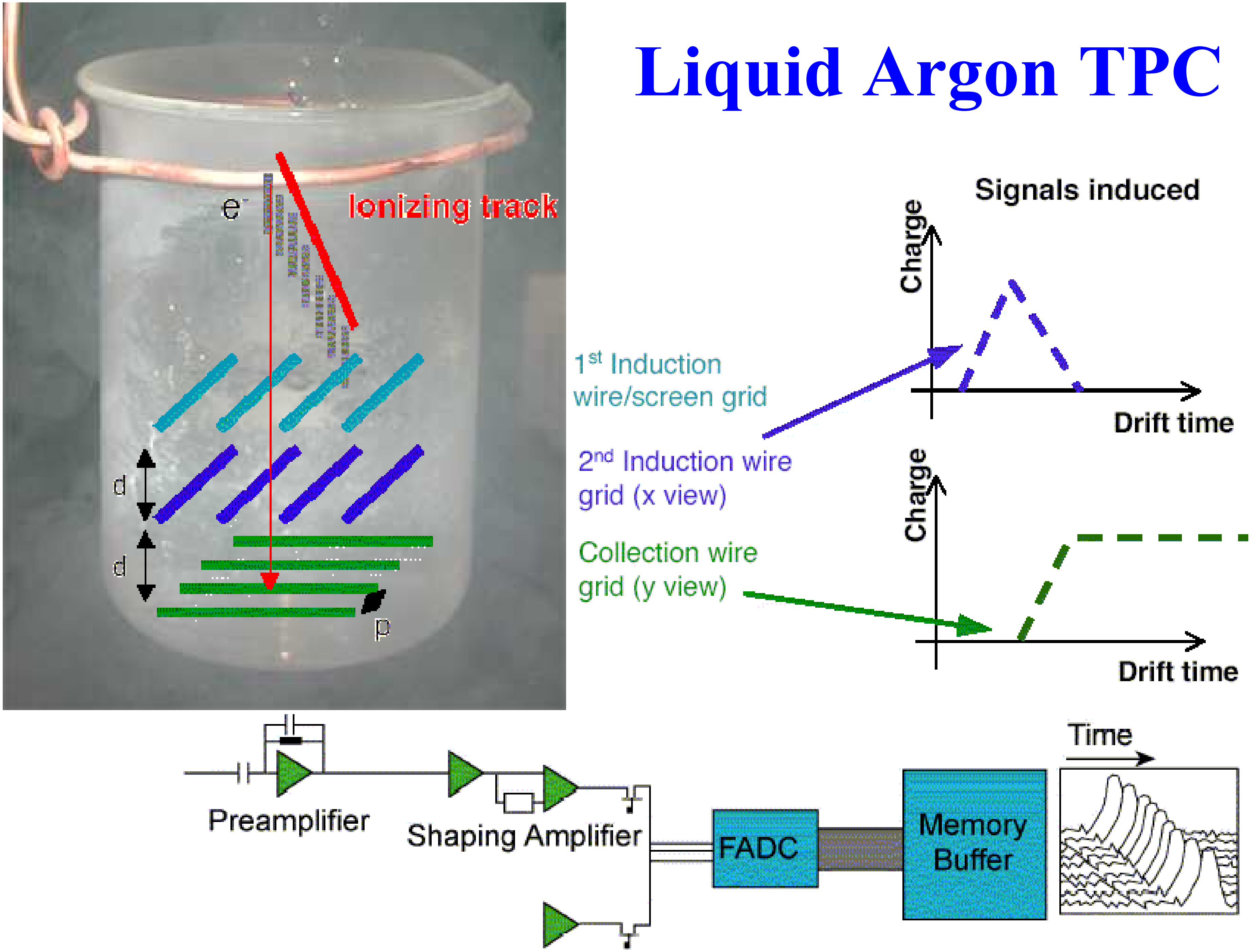
2.7 tons drift chambers target
Density (g/cm^3) 0.1
2% X_0/chamber
0.4 T magnetic field

TRD detector
Lead glass calorimeter

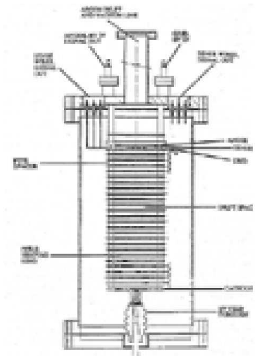


Resolution (mm^3)	2×2×0.2
Density (g/cm^3)	1.4
X_0 (cm)	14.0
λ_T (cm)	54.8
dE/dx (MeV/cm)	2.1

Liquid Argon TPC

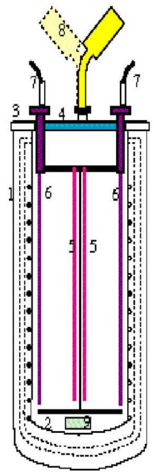


ICARUS R&D steps



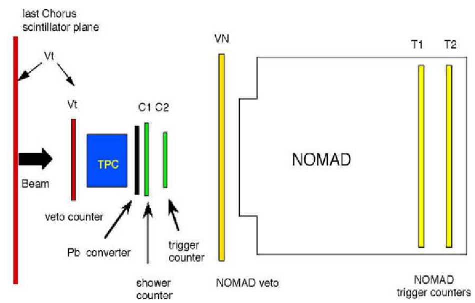
24 cm drift wires chamber

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.



3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



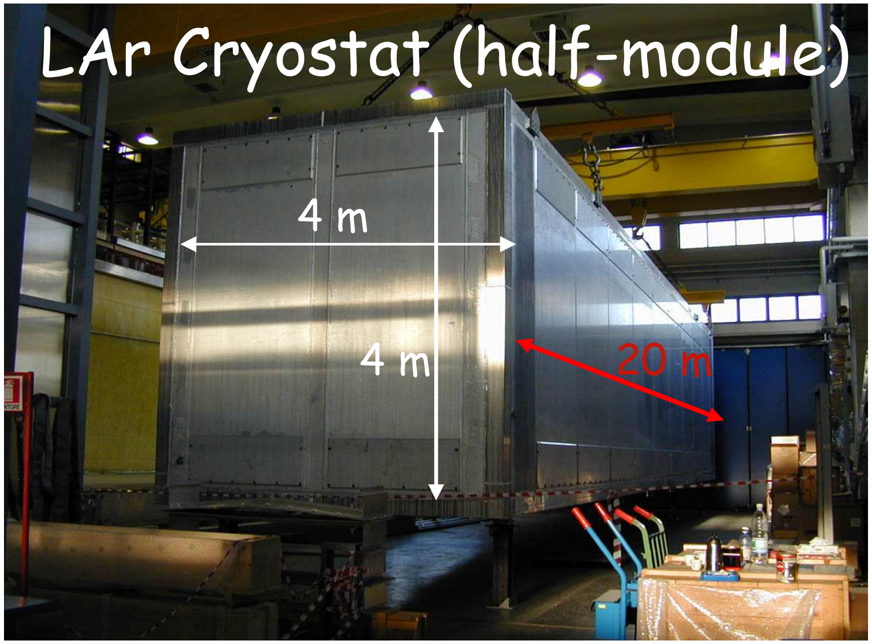
50 litres prototype
1.4 m drift chamber

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

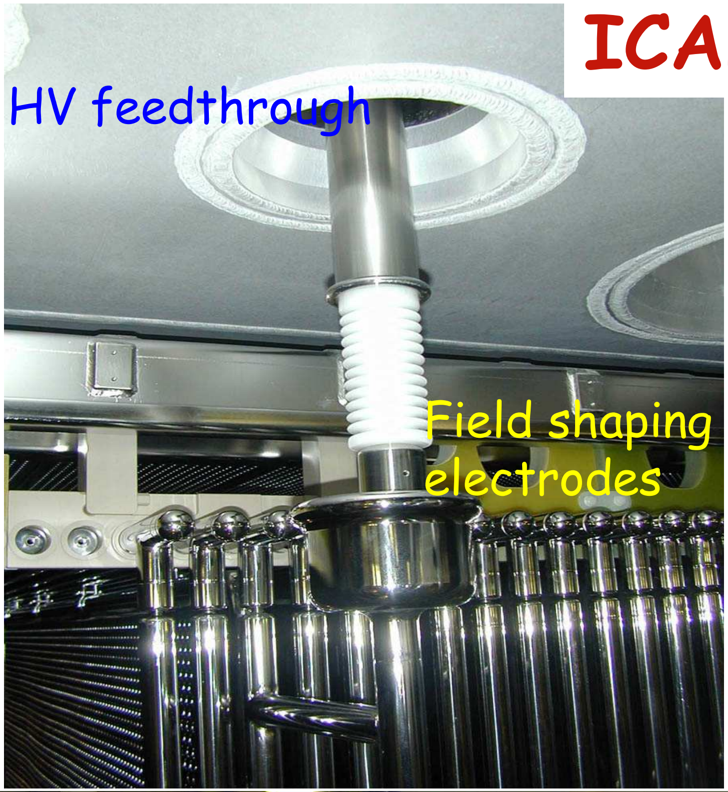
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

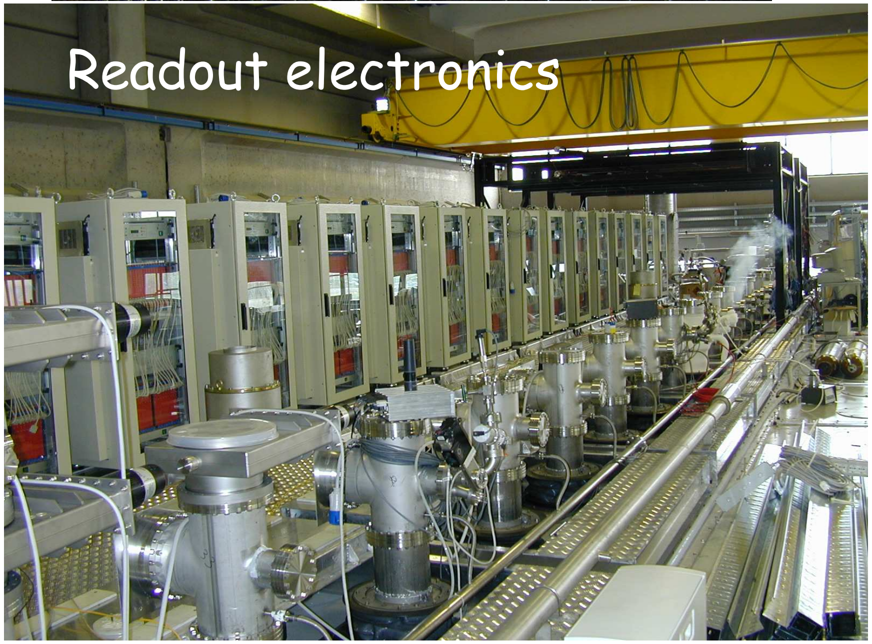
T300 cryostat

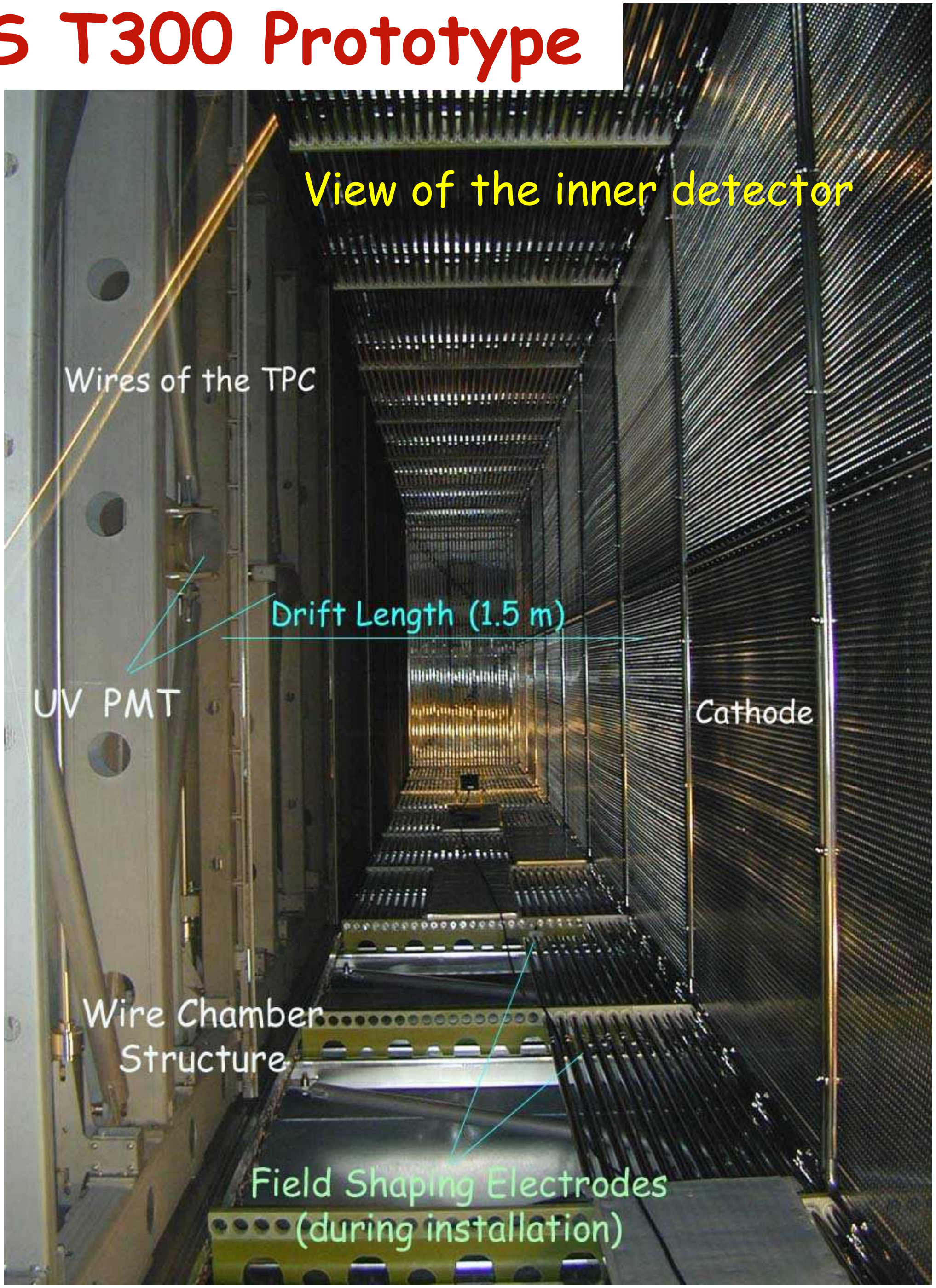


- T300 is a half-module of the T600
- cryostat constructed out of 15 cm thick panels, made of aluminum honeycomb sandwiched between aluminum skins
- thermal insulation panels, 0.5 m thick, made of Nomex (pre-impregnated paper) honeycomb
- cooling performed by circulating LN_2 inside cooling circuits placed immediately outside of the cryostat
- possibility to evacuate the cryostat down to 10^{-4} mbar
- … but relatively large thermal losses, up to 22 W/m^2

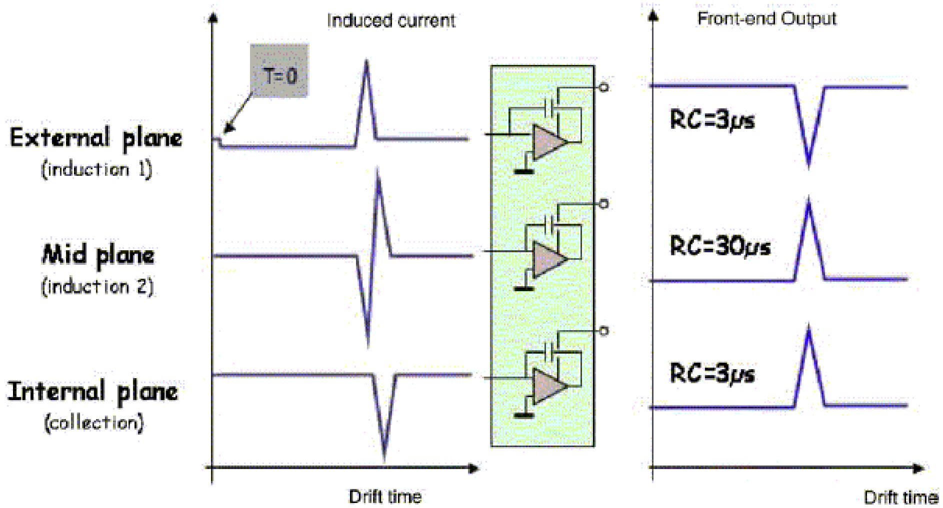
ICARUS T300 Prototype

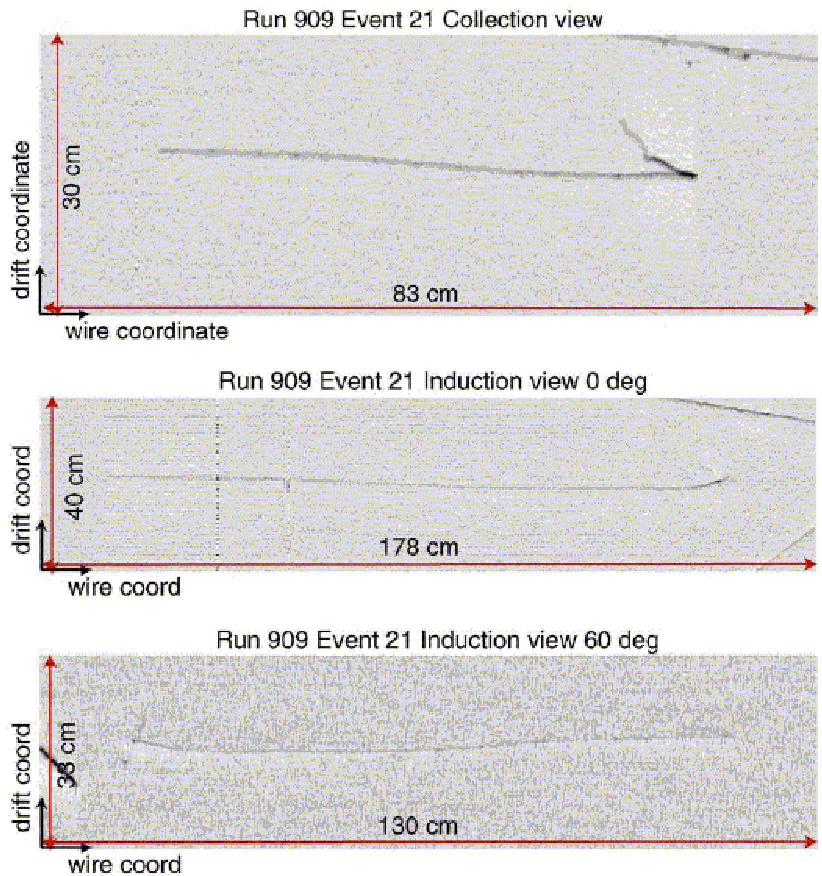






Signals and event reconstruction from T300





- 3 wire planes (0°, ±60°), 3 mm wire pitch, 3 mm distance between wire planes
- 0° wires: 9.4 m long, ±60° wires: 3.8 m
- input capacitance (wire+cable)
  0° wires: ~400 pF, ±60° wires: ~200 pF

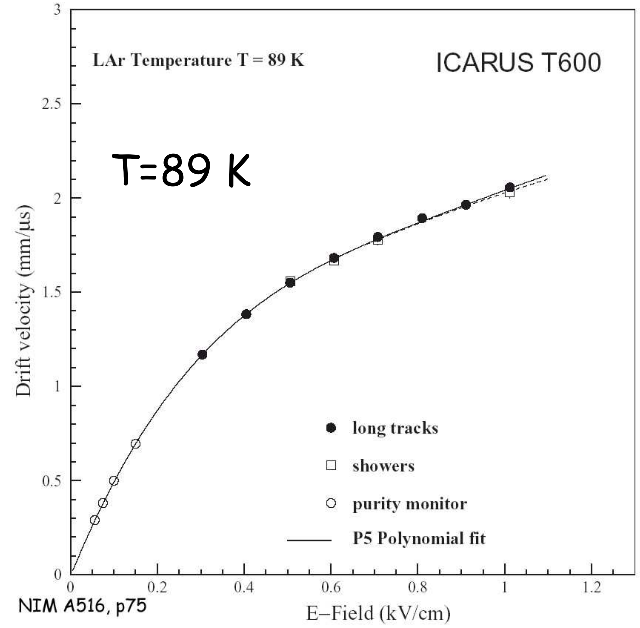
- ionization signal: 5500 e/mm @ 500 V/cm (before attenuation due to drift)
- Equivalent Noise Charge $Q_{noise}=(500+2.5\times C_{input}\ [pF])$ electrons
- Signal/Noise ratio: ~ 10
- each wire digitized at 2.5 MHz by a 10 bit Flash ADC

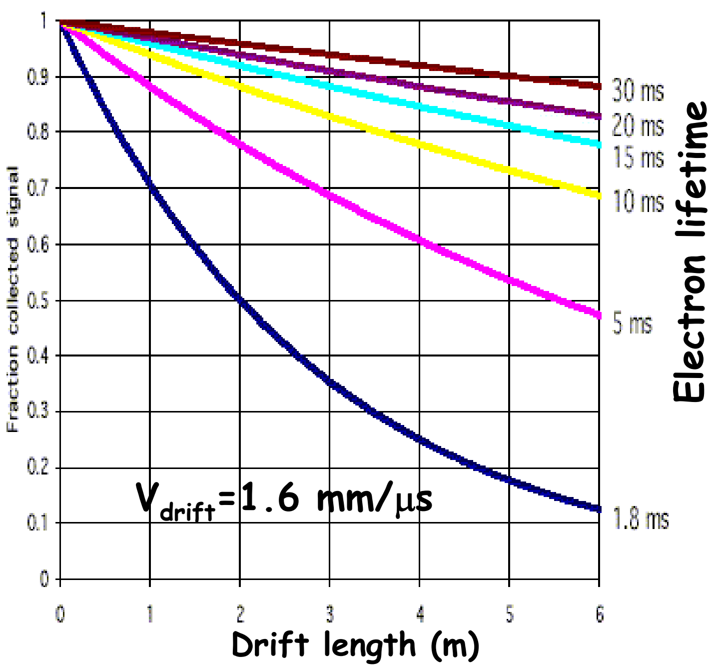
Can we drift over over long distances (3m) ?

- HV feedthrough tested by ICARUS up to 150 kV (E=1kV/cm in T600)
- v_{drift}= (1.55±0.02) mm/μs @ 500 V/cm
- Diffusion of electrons:

$$\sigma_d = \sqrt{2 \times D \times t}, D = 4.8 \pm 0.2 cm^2 s^{-1}$$

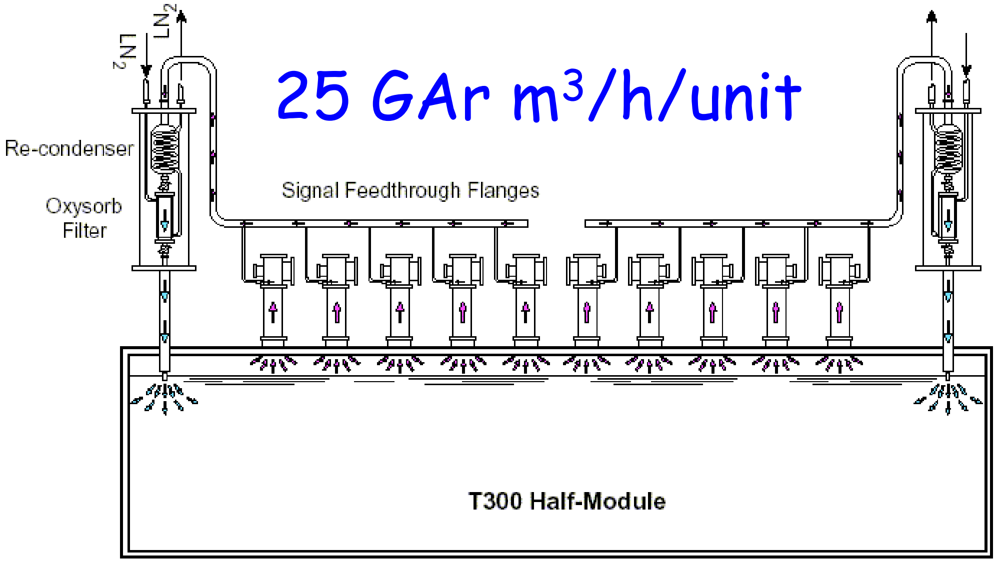
σ_d=1.4 mm for t=2 ms



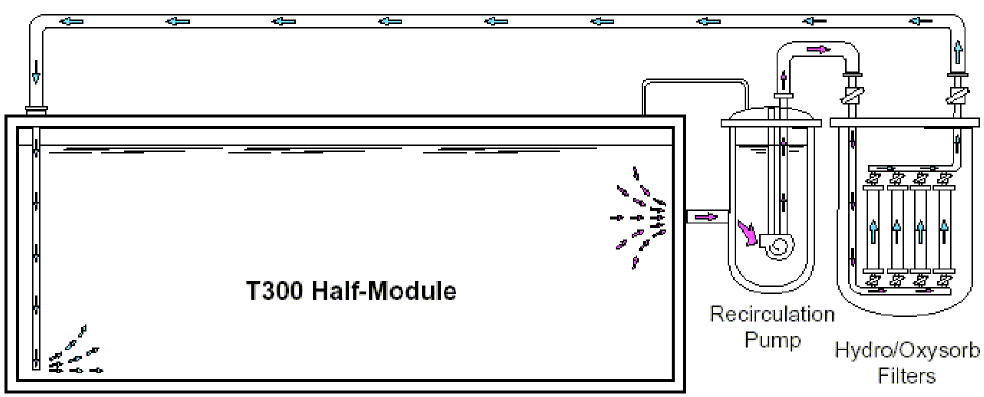


- to drift over macroscopic distances, LAr must be very pure
  - a concentration of 0.1 ppb Oxygen equivalent gives an electron lifetime of 3 ms
- for a 3 m drift and <20% signal loss we need an electron lifetime of 10 ms

Argon purification in ICARUS



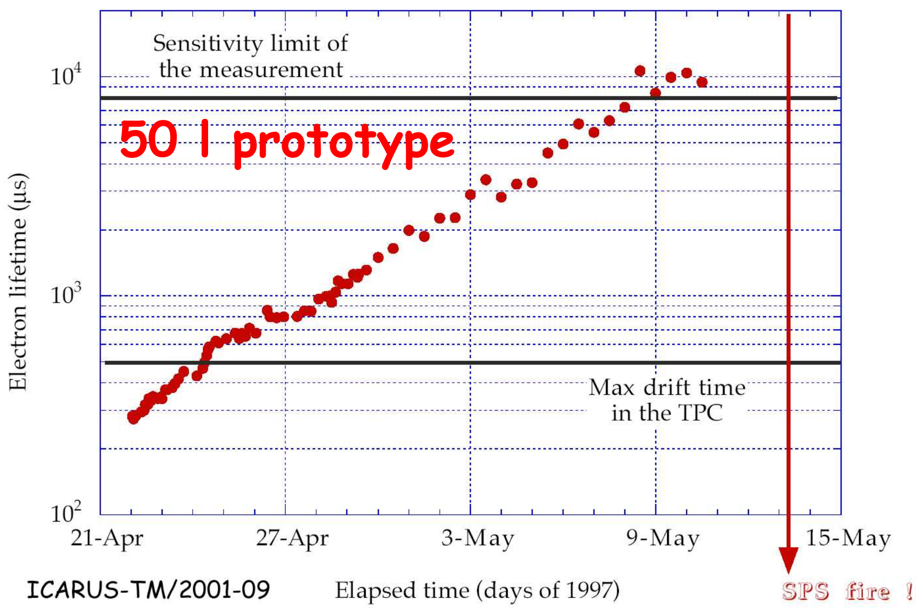
Recirculate gaseous and liquid Argon through standard Oxysorb/Hydrosorb filters



2.5 LAr m^3/h

It was verified that LAr recirculation system does not induce any microphonic noise to the wires, so it can be active during the operation of the detector

Argon purity, electron lifetime in ICARUS



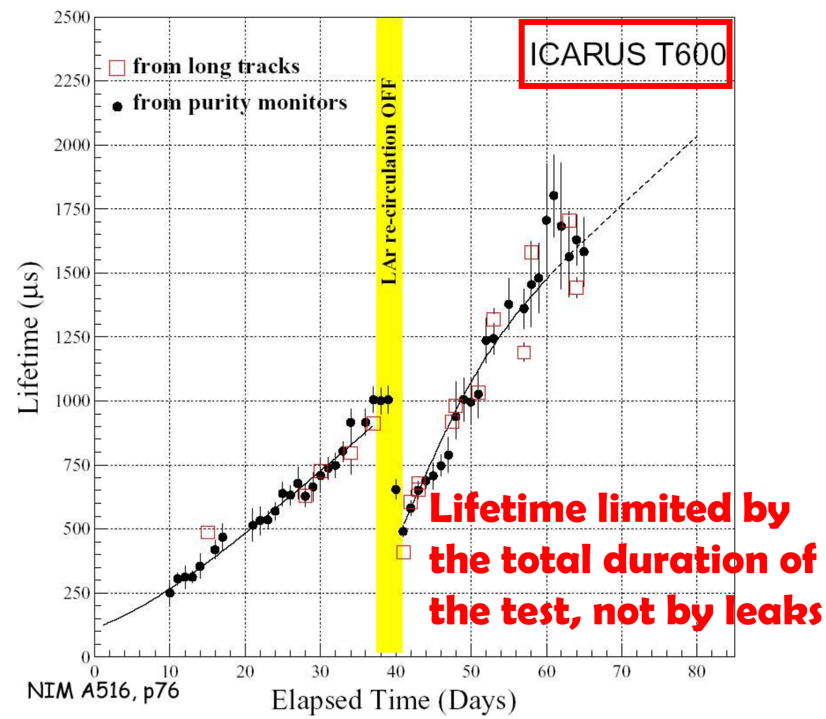
The concentration of impurities, N, is determined by

- constant input rate of impurities (leaks) Φ_{in}^{0}
- outgassing of material A, B
- purification time τ_c

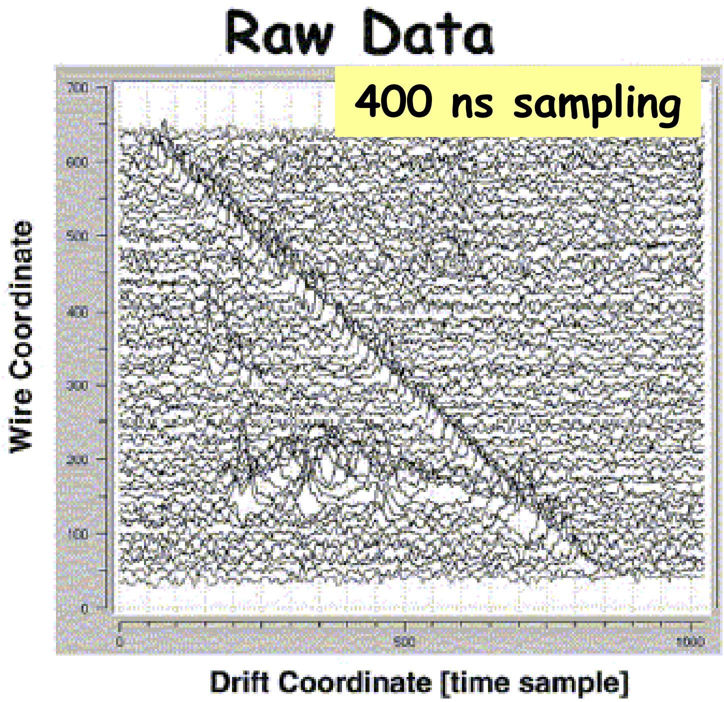
$$\frac{dN}{dt} = -\Phi_{out}(t) + \Phi_{in}(t) =$$

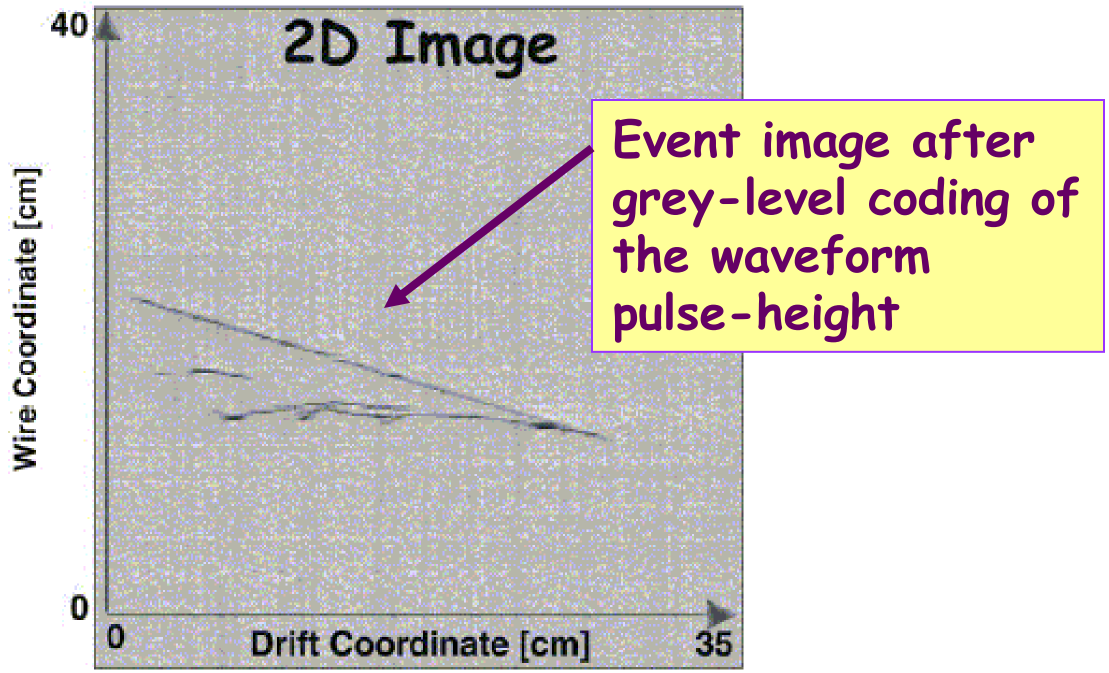
$$-\frac{N(t)}{\tau_c} + \Phi_{in}^{0} + \frac{A}{(1+t/t_0)^B}$$

Φ_{in}^{0}= (5±5)×10^{-3} ppb/day oxygen
A=0.33±0.07 ppb/day
B=1.39±0.05



Learnings from ICARUS





- demonstration of 3D imaging reconstruction over massive detector volumes (~ 1 kton)
  - performance comparable to traditional bubble chambers, with the advantage of being continuously sensitive
- calorimetric measurement, particle ID capabilities
- possibility of absolute timing definition and internal trigger from LAr scintillation light detection

Lessons from ICARUS for a very large detector (tens of kton)

- **Importance of the cryostat design**
  - not to pollute Argon (no leaks)
  - to maintain stable thermodynamic conditions (good insulation)
- **Possibility to safely employ high voltages up to 150 kV**
- **Reliability of the chamber design** … no broken wires during the transportation of the T600 module from Pavia to Gran Sasso on italian highways
- **Long electron lifetimes (>5 ms)/drift distances (> 1.5 m) appear achievable**
  - after the initial phase, main sources of impurities are the surfaces exposed to the gaseous Argon
  - better volume/surface ratio in a larger detector
  - both Gar and LAr recirculation systems are needed

LArTPC's report to NuSAG*

Fermilab Note: **FN-0776-E**

A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis
Neutrino Oscillation Physics with the NuMI Beam
Submission to NuSAG
September 15, 2005

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* The Neutrino Scientific Assessment Group for the DOE/NSF

Soon to be on the hep-ex preprint server

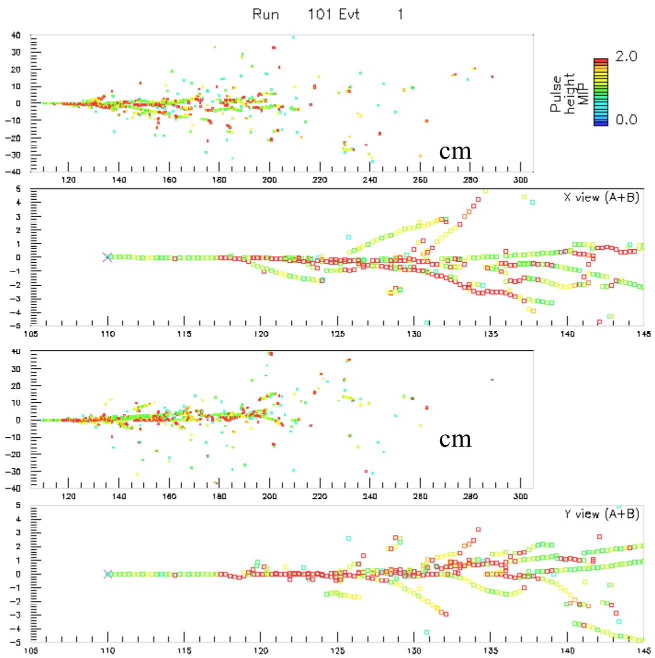
The promise of LAr

Electrons compared to π^0's at 1.5 GeV in LAr TPC

Dot indicates hit, color is collected charge
green=1 mip, red=2 mips (or more)

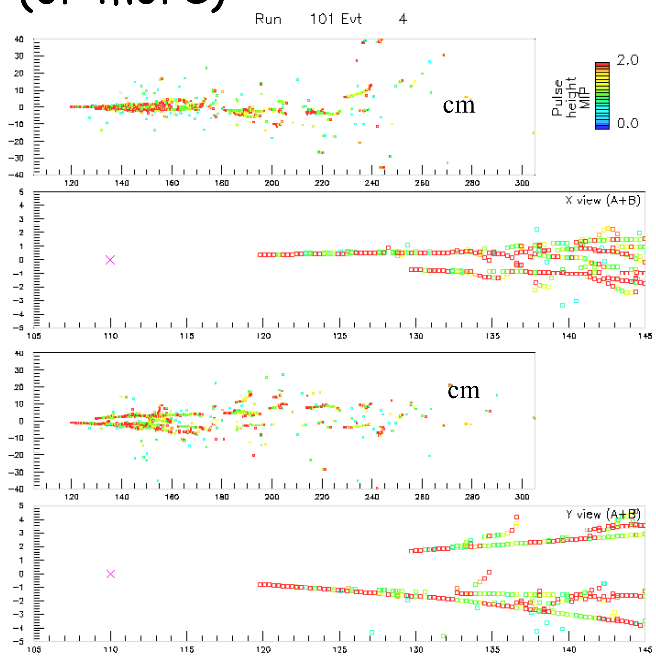
X plane → zoom in

U plane → zoom in



X plane → zoom in

U plane → zoom in



Electrons

Single track (mip scale)
starting from a single vertex

π^0

Multiple secondary tracks pointing back to the same primary vertex

Each track is two electrons
- 2 mip scale per hit

use both topology and dE/dx to identify interactions

The promise of LAr

Neutral current event with 1 GeV π^0

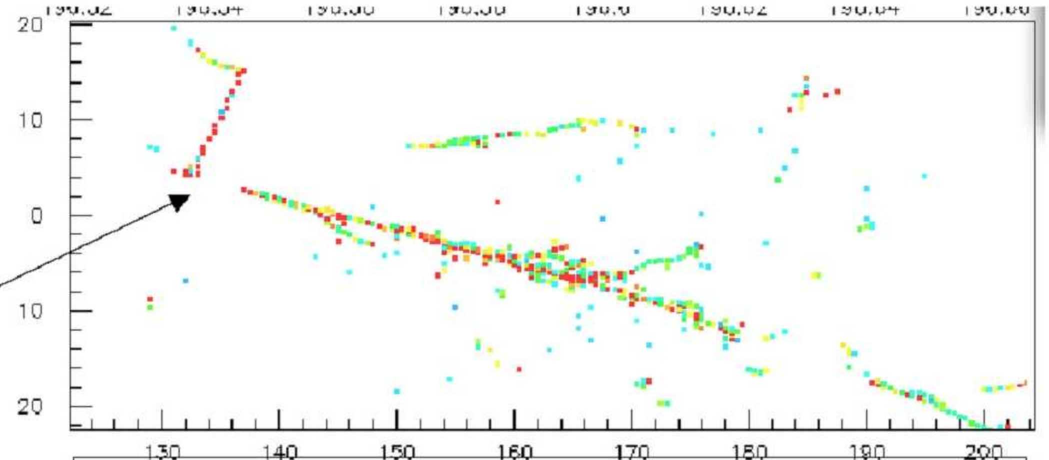
$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

$$(1\ \mathrm{GeV})\ \pi^0 \rightarrow \gamma + \gamma$$

3.5% X_0 samples

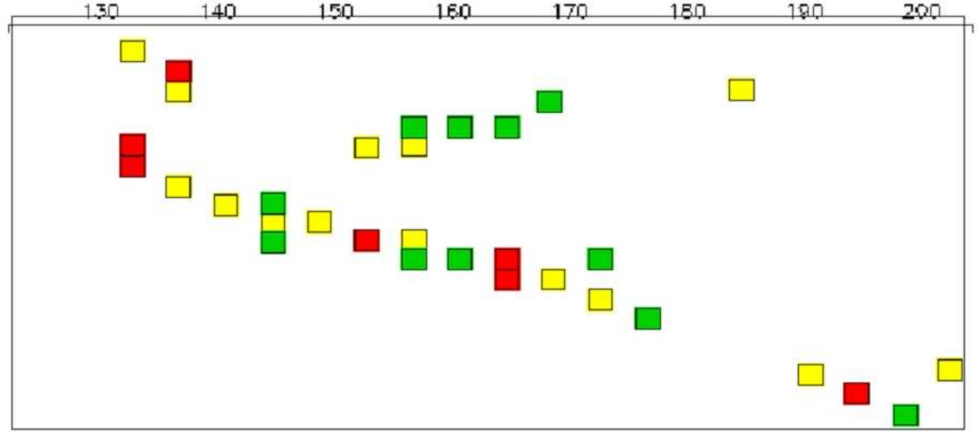
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y



Efficiency and rejection study

Tufts University Group

Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of "signal" events by experts.

Neutrino event generator: NEUGEN3, used by MINOS/NOvA collaboration (and others) Hugh Gallagher (Tufts) is the principal author.

GEANT 3 detector simulation (Hatcher, Para): trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

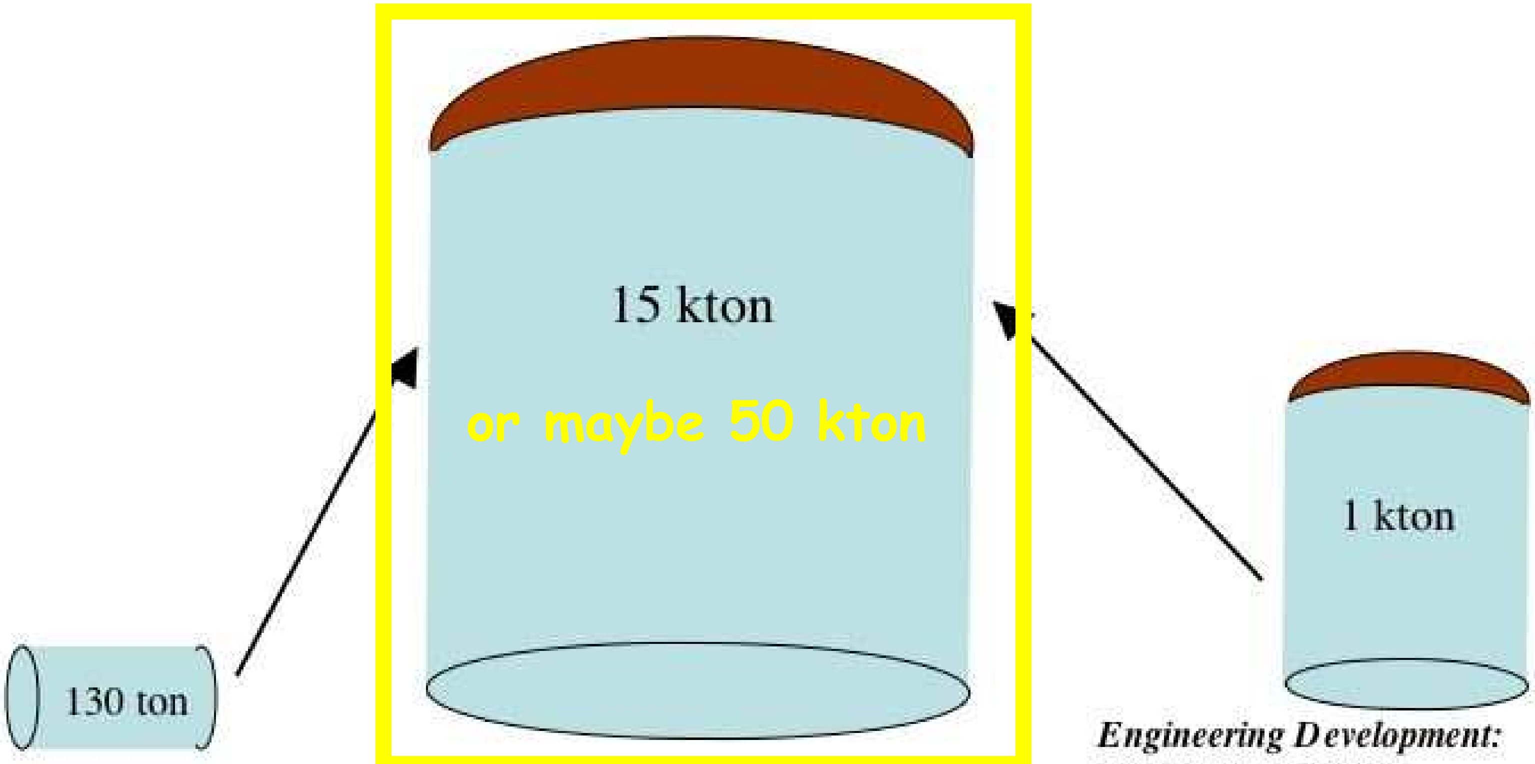
signal efficiency — background rejection

Event Type		N	pass	ϵ	η
NC		290	4	-	0.99 ± 0.01
signal ν_e	CC	32	26	0.81 ± 0.07	-
Beam ν_e	CC	24	14	0.58 ± 0.10	-
Beam ν_e	NC	8	0	-	/
Beam $\overline{\nu}_e$	CC	13	10	0.77 ± 0.09	-
Beam $\overline{\nu}_e$	NC	19	0	-	/
ν_μ	CC	32	0	-	/
$\overline{\nu}_\mu$	CC	32	1	-	/

+ factor of 6 rejection on NC background from energy pre-selection $\Rightarrow$ 99.8% NC rejection efficiency

Good signal efficiency (81±7)%

NuMI LAr TPC overview



Engineering Development:
Construction of Tank
Argon Purity
Mechanical Integrity of TPC
Readout S/N
Microphonics due to Argon Flow

Physics Development *using* ***existing*** *technology*
Record **complete neutrino interactions**: (ν_e & ν_μ)
Establish **Physics Collaboration**
Develop **Event Identification**,
Develop **Reconstruction**,
Develop **Analysis**,
Establish successful **Technology transfer**

Technical Setups

Purity Monitor Development	Materials Tests	5 m Drift Demonstration	Long Wires Tests	Electronics Development

A 15 –50 kton LAr Detector

Basic concept follows ICARUS:

TPC, drift ionization electrons to 3 sets of wires (2 induction, 1 collection)
record signals on all wires with continuous waveform digitizing electronics

Differences aimed at making a multi-kton detector feasible

Construction of detector tank using industrial LNG tank as basic structure
Long(er) signal wires
Single device (not modular)

Basic parameters:

Drift distance - 3 meters; Drift field - 500 V/cm (gives v_{drift} = 1.5 m/ms)
High Voltage 150 kV
Wire planes - 3 (+/-30^0 and vertical); wire spacing 5 mm; plane spacing 5 mm
Number of signal channels ~ 100,000 (15kt), 220,000 (50kt)

A 15 –50 kton LAr Detector

Some Specific challenges:

3 m drift in LAr

purification - starting from atmosphere (cannot evacuate detector tank)

- effect of tank walls & non-clean-room assembly process

Wire-planes:

long wires - mechanical robustness, tensioning, assembly, breakage/failure

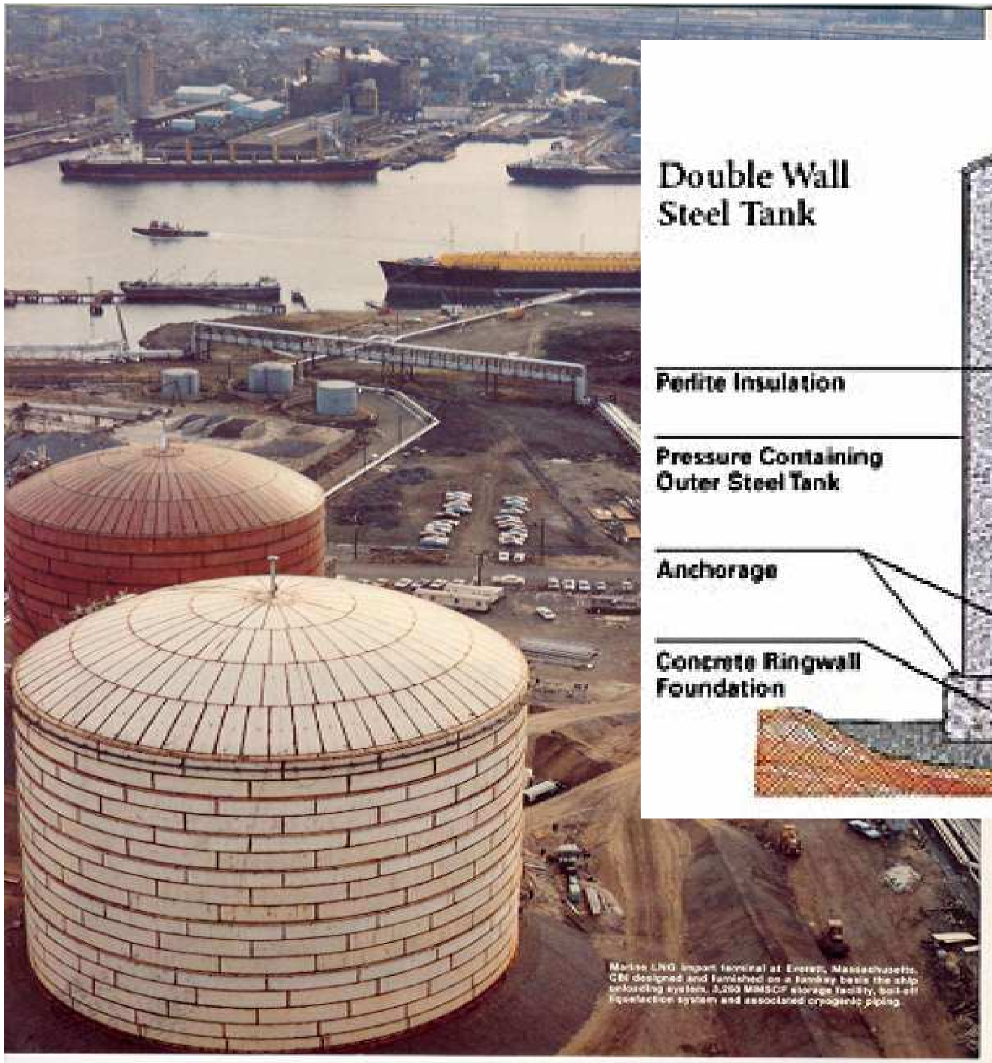
Signal processing:

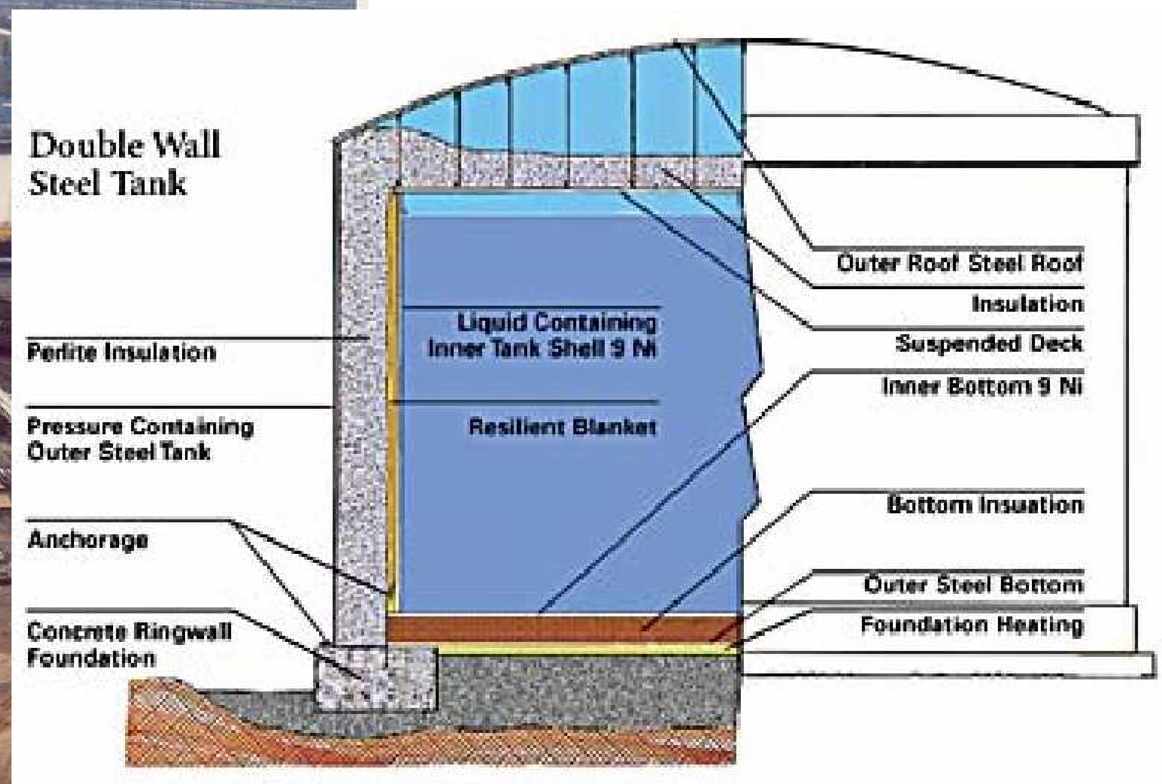
electronics - noise due to long wire and connection cables (large capacitance)

surface detector - data-rates,

- automated cosmic ray rejection
- automated event recognition and reconstruction

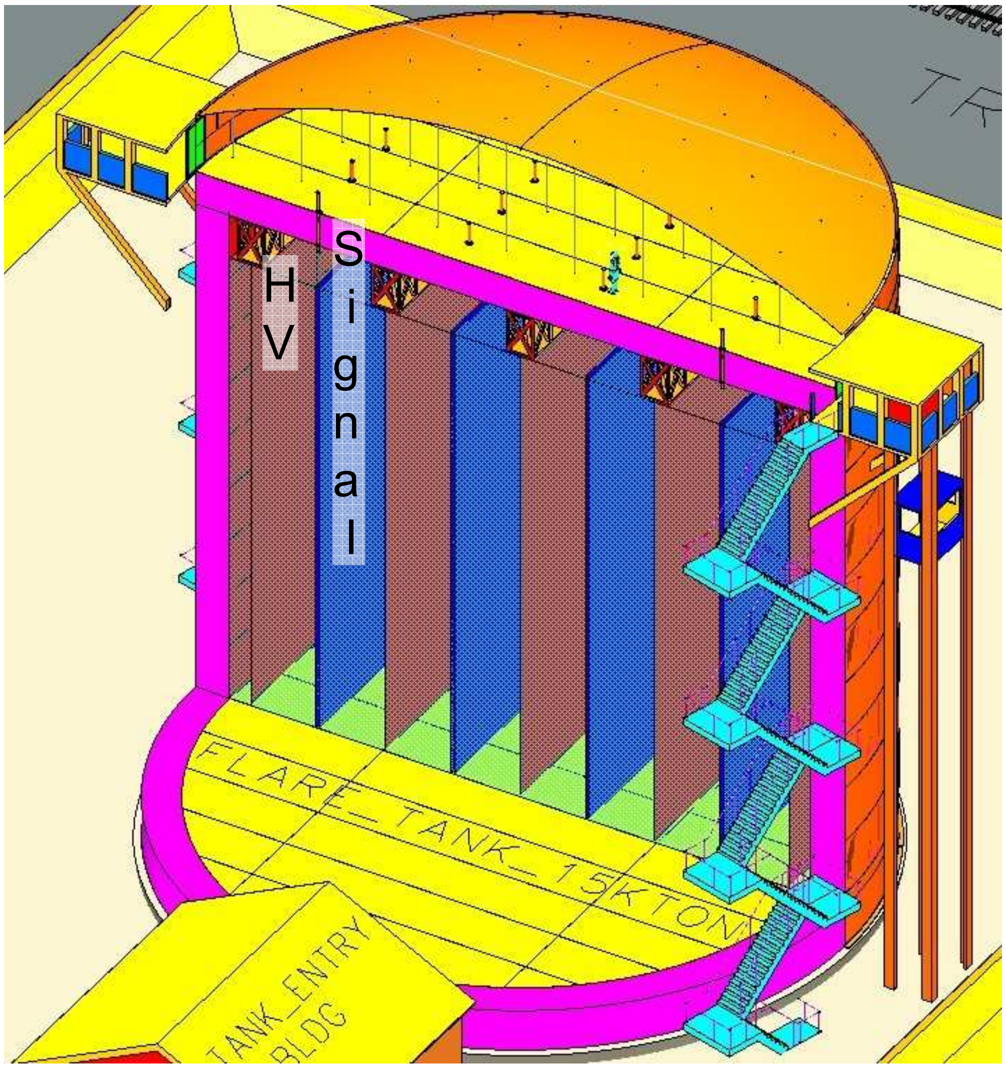
Detector Tank based on Industrial Liquefied Natural Gas (LNG) storage tanks





Many large LNG tanks in service. excellent safety record

The large LAr TPC: a sketch



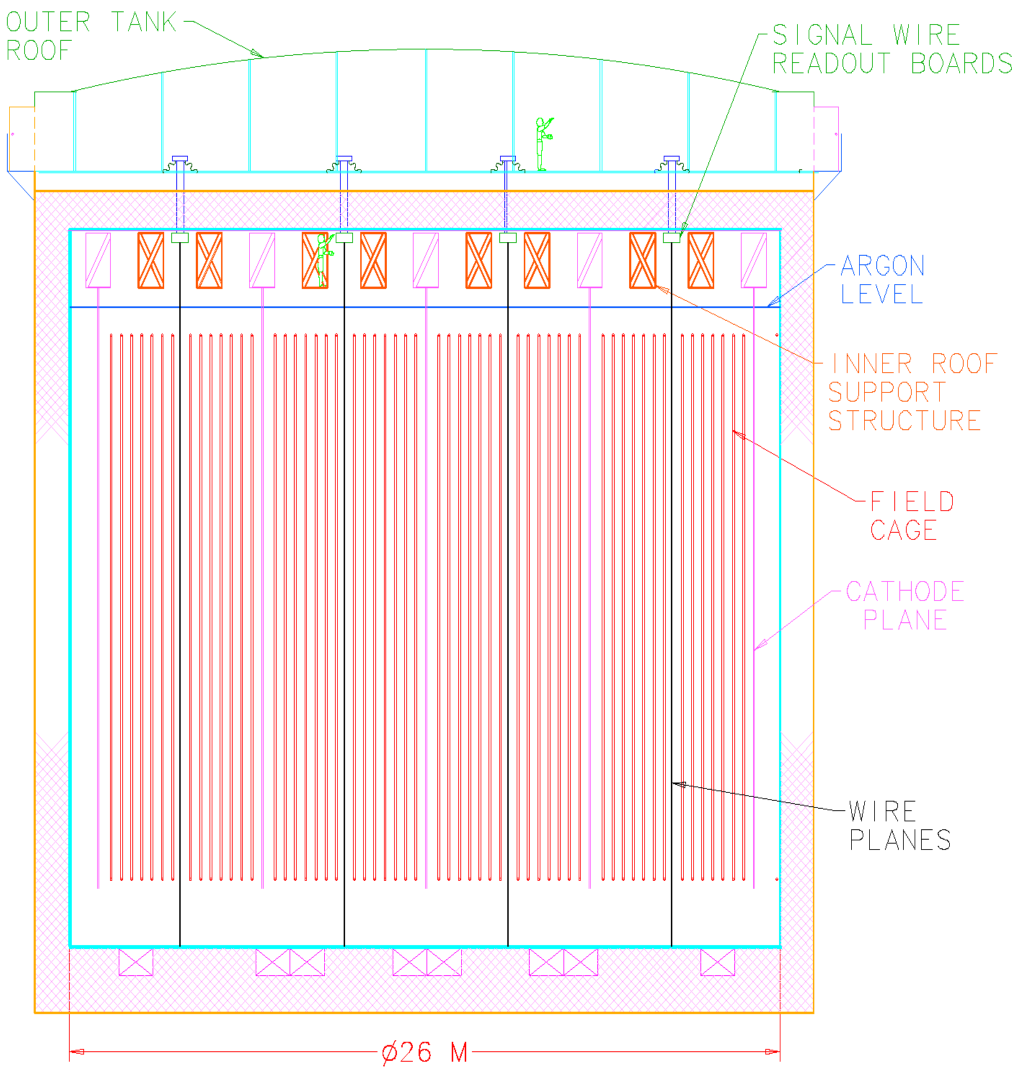
3D `Model' cutaway
15 kt detector

Inner tank dimensions
26 m ∅, 21 m height

Changes from standard LNG tank:

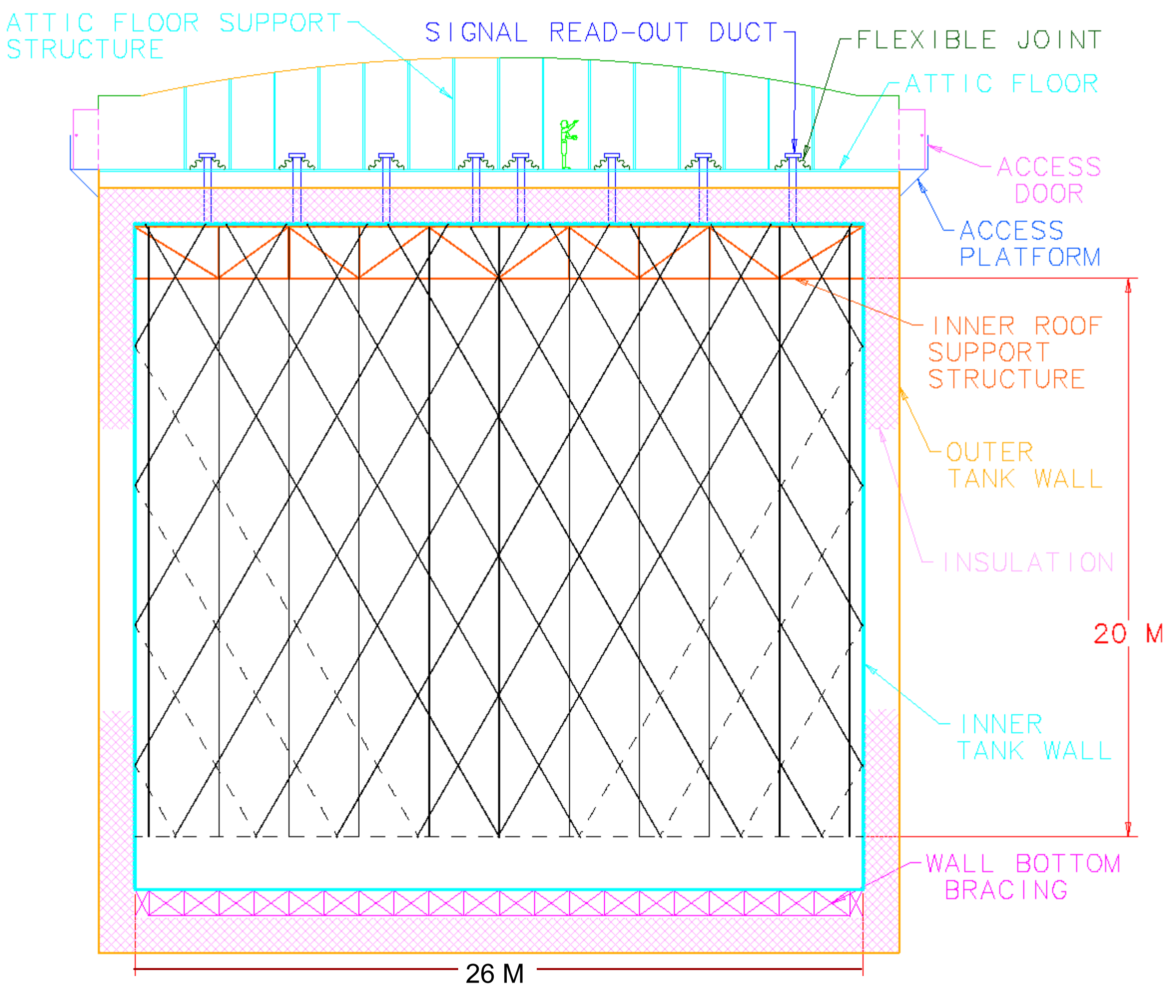
- inner tank wall thickness increased
  - LAr is 2 x density of LNG;
- trusses in inner tank to take load of the wires;
- penetrations for signals from inner tank to floor supported from roof of outer tank.

The large LAr TPC: Beam's Eye View



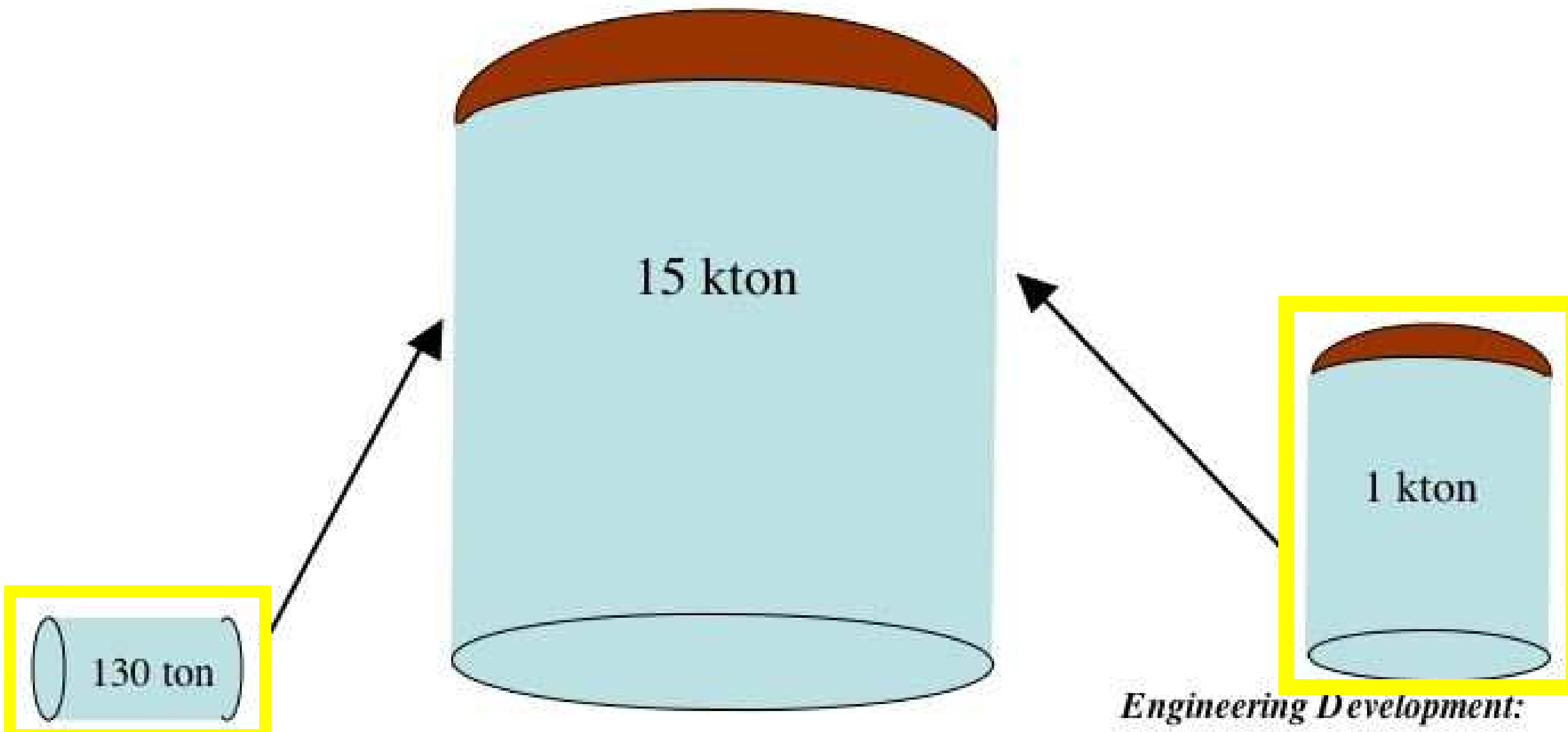
Beam's eye view showing the electrodes (cathode, field-cage and wires)

The large LAr TPC: side view



side view: showing trusses & signal chimneys:
only wires reaching the top (solid lines) are read out.

The R&D path



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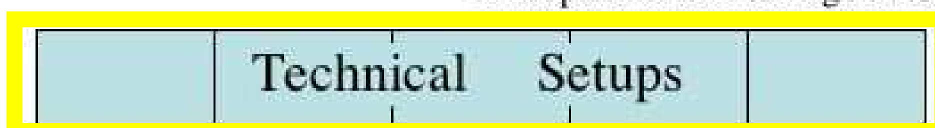
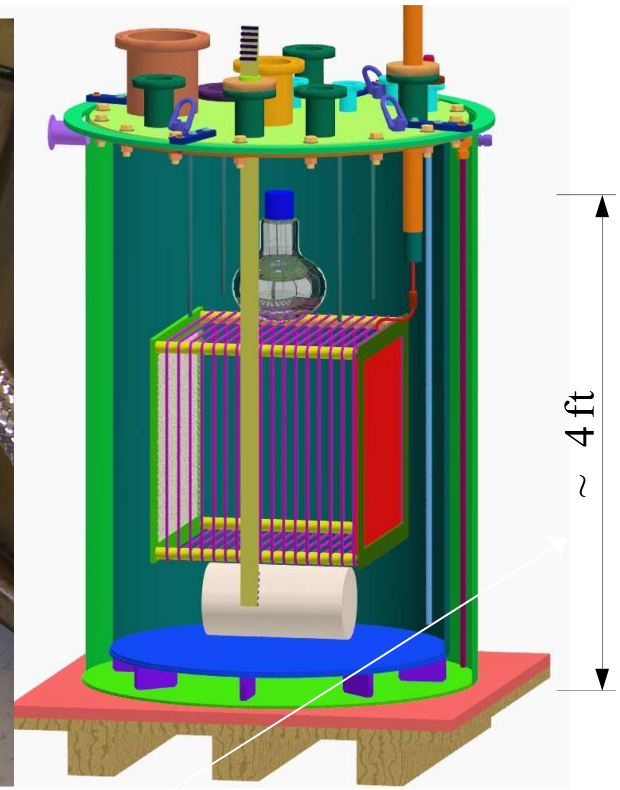


Purity Monitor Development | Materials Tests | 5 m Drift Demonstration | Long Wires Tests | Electronics Development

LAr TPC Test Setup @ Yale

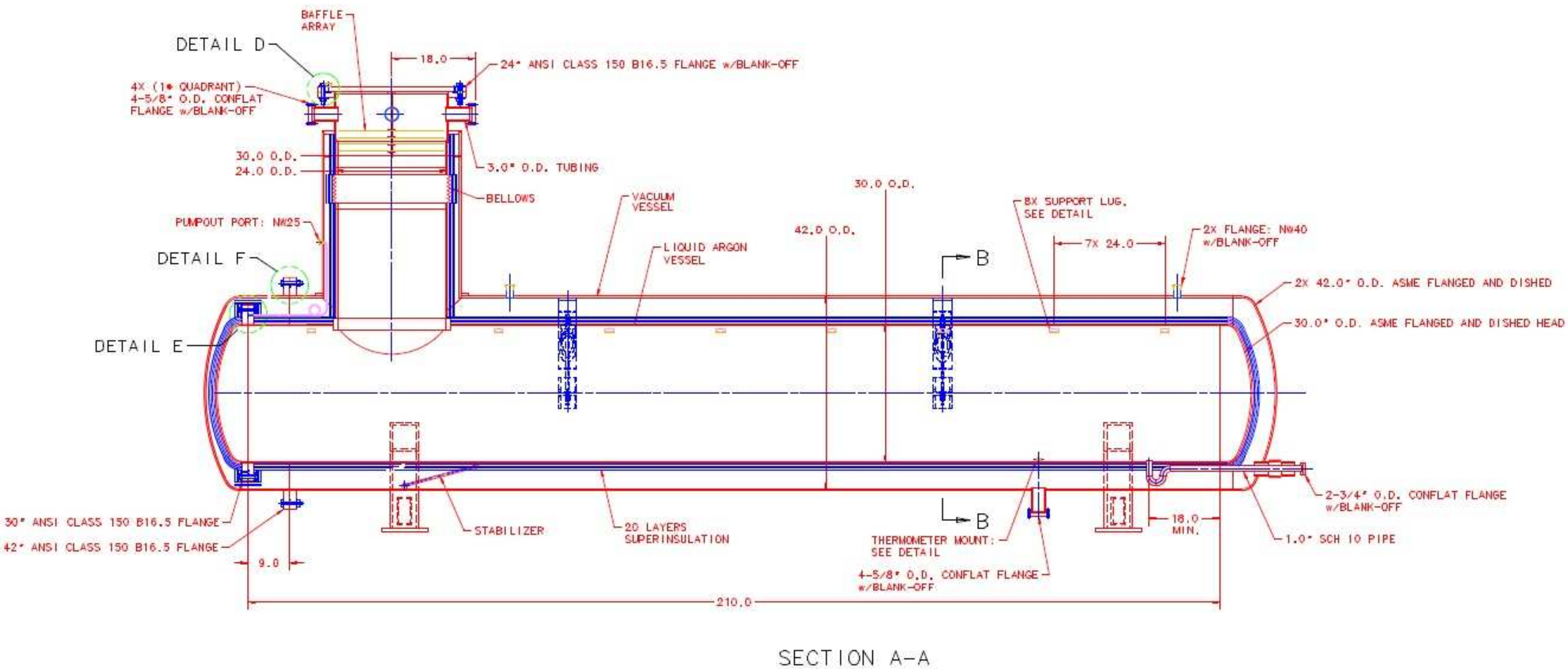
Purity monitor in liquid argon



Purity and light collection

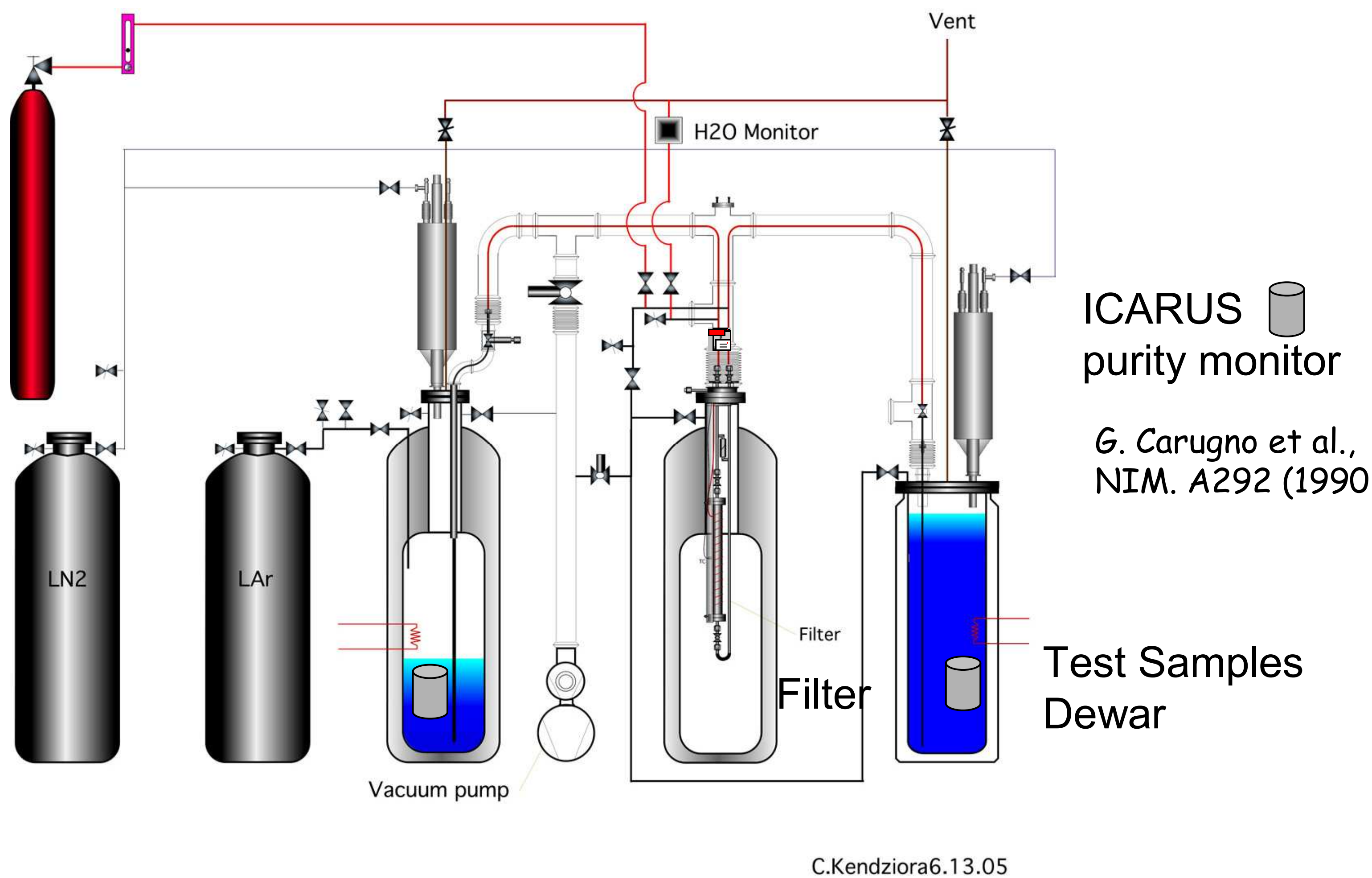
5 m Drift Demonstration at Fermilab

Cryostat drawing for purchasing department



Material tests

System at Fermilab for testing filter materials and the contaminating effects of detector materials (e.g. tank-walls, cables)



Material tests

setup for lifetime measurements (effect of materials and effectiveness of different filters) under assembly at Fermilab

Long wires tests

- **Wire Planes:**
  - Induction (2 +/- 30) and Collection Planes spaced by 5 m
  - 5mm pitch within planes
  - ~220,000 signal wires total (50 kTon), ~100,000 signal wires (15 kTon)
  - Longest wire ~35 meters (50 kTon) , ~ 23 meters (15 kTon)

- Need to be robust - no breakages
- Need practical assembly and installation procedure.

- Wire Material 150 micron Stainless Steel

- **Present Concept: (different from ICARUS)**
  - Tension implemented by attaching a weight to each wire (~1kg) to avoid tension changes due to temperature changes.
  - Looking for alternative simpler ways

The Purposes of the "130 ton" detector (50 ton fiducial)

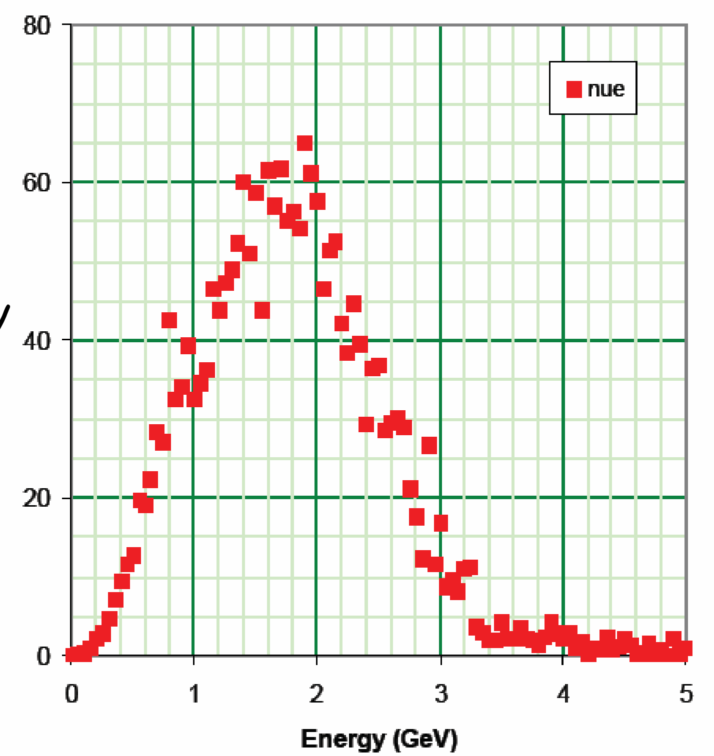
- **Physics development using existing technology**
  - **Establish successful technology transfer**
  - **Record complete neutrino interactions (ν_μ and ν_e) in the presence of cosmic rays**
  - Establish physics collaboration by:
    - Developing event identification
    - Developing reconstruction
    - Developing analysis
  - **Measure ν interactions in the quasi-elastic and resonance region (?)**

Where to find 2 GeV electrons ?

Electron Neutrinos in MINOS Surface Building

From the NOvA Proposal March 15, 2005

ν_e CC events / 50 MeV



- The charged current ν_e event spectrum in the MINOS surface building.
- The ν_e event spectrum peaks just below 2 GeV.
- There are ~2,000 ν_e events shown here for 6.5E20 POT and the 20.4 ton fiducial mass NOvA near detector.

NuMI is presently providing ~2E20 POT per year.

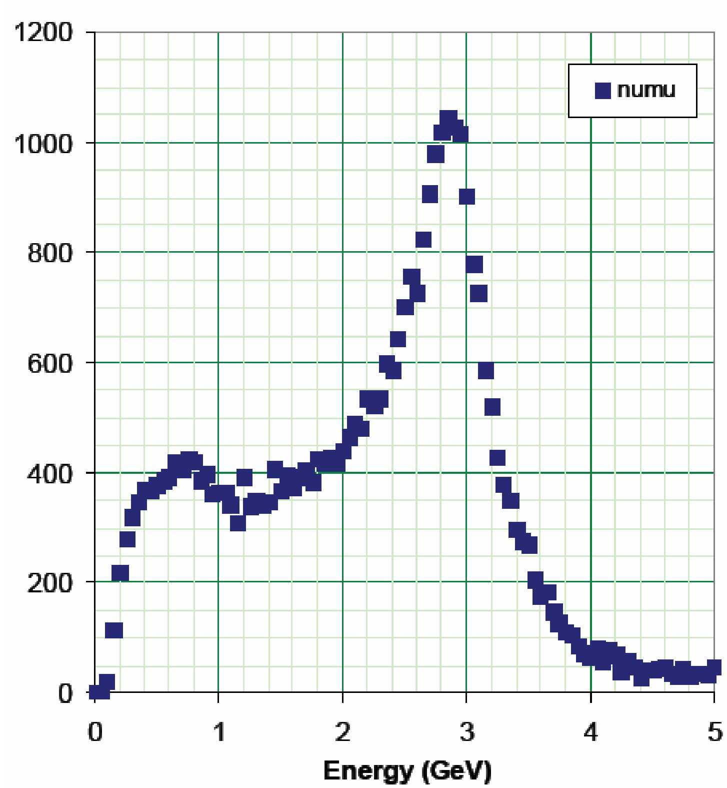
The 130 ton LArTPC has a 50 ton fiducial mass.

➥ **the LAr TPC detector would get ~1500 ν_e events / year.**

Muon Neutrinos in MINOS Surface Building

From the NOvA Proposal March 15, 2005

ν_μ CC events / 50 MeV



- Same assumptions as previous slide, except this shows ~15,000 muon neutrinos.
- The ν_μ peak at ~2.8 GeV is from Kaon decay.

➥ **the LAr TPC detector would get ~11000 ν_μ events / year.**

The Purposes of the "1 kton" tank

- **Engineering Development to demonstrate scalability to large tank**

  - **Construction of tank with the same techniques to be used with the large tank**
  - **Demonstrate argon purity with the same techniques to be used with the large tank**

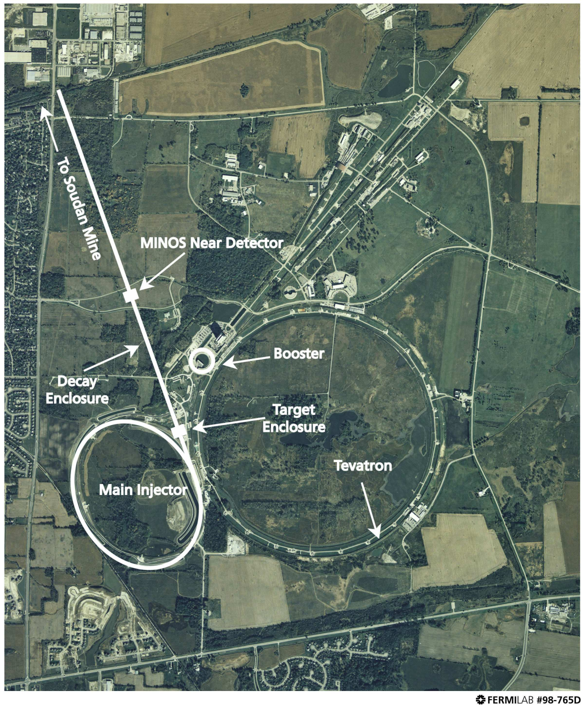
  - **Mechanical integrity of TPC**
  - **Readout signal / noise**
  - **Microphonics due to argon flow**

  - **Uncover whatever surprises there may be**

Conclusions

- We need larger and more efficient detectors to fully exploit the physics opportunities made available by the NuMI neutrino line
- Impressive results from the ICARUS T300 prototype
- We have an R&D plan to demonstrate scalability of LAr technology for tens of kton detectors
  - Receiving generous support for technology transfer from experts in Europe
  - Receiving support from Fermilab, both in engineering and with recently increased funding
  - Growing support from University groups in smaller technical setups, software efforts, …
- Beginning a study to fully understand all the physics capabilities offered by a tens of kton LAr detector, maybe in conjunction with the NoVA detector

Would like to develop our efforts with wider participation



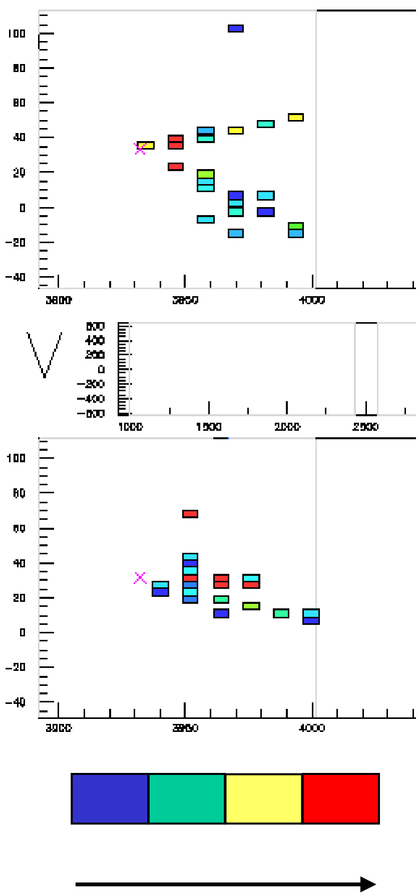
Main Injector & NuMI

- **Main Injector is a rapid cycling (up to 204 GeV/c/s) accelerator at 120 GeV**
  - from 8 to 120 GeV/c in ~ 1.5 s
- **up to 6 proton batches (~ 5×10^{12} p/batch) are successively injected from Booster into Main Injector**
- **Main Injector has to satisfy simultaneously the needs of the Collider program (anti-proton stacking and transfers to the Tevatron) and NuMI**
- **total beam intensity ~ 3×10^{13} ppp, cycle length 2 s**

- **Mixed mode: NuMI & anti-proton stacking**
  - two single turn extractions within ~ 1 ms:
    - 1 batch to the anti-proton target, following the firing of the MI52 kicker
    - 5 batches to NuMI, following the firing of the NuMI kickers, in ~ 8 μs
  - the batch extracted to the anti-proton target comes from
    - either a single Booster batch
    - **or the merging of two Booster batches ("slip-stacking") (up to 0.8×10^{13} ppp)**
  - ***the default mode of operation is mixed-mode with slip-stacking***
- **NuMI only**
  - up to 6 Booster batches extracted to NuMI in ~ 10 μs

ν_e Interactions in MINOS ?

NC interaction

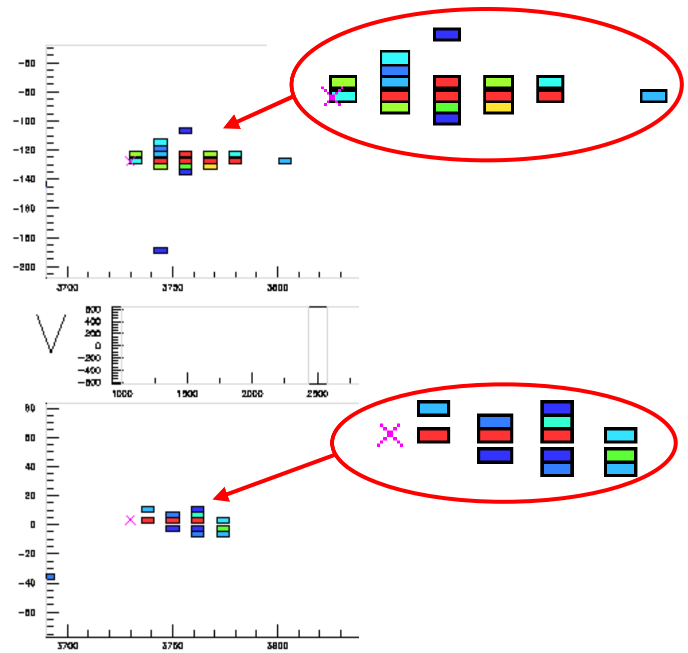


energy

Detector Granularity:

- Longitudinal: $1.5X_0$
- Transverse: $\sim R_M$

ν_e CC, E_{tot} = 3 GeV



- **NC interactions**
  - energy distributed over a 'large' volume
- **ν_e CC interactions (low y)**
  - electromagnetic shower short and narrow
  - most of the energy in a narrow cluster

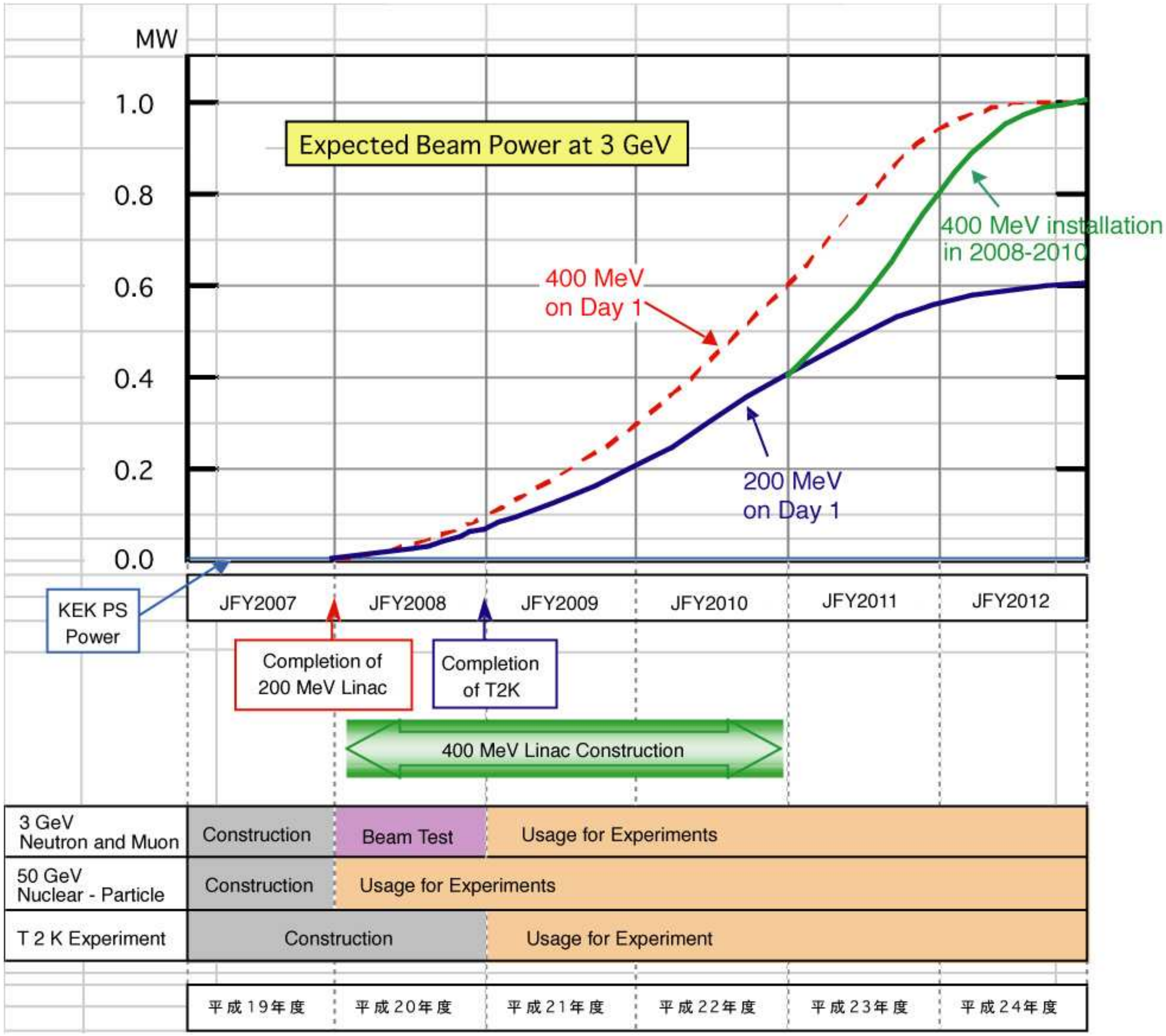
NoVA cost

Cost

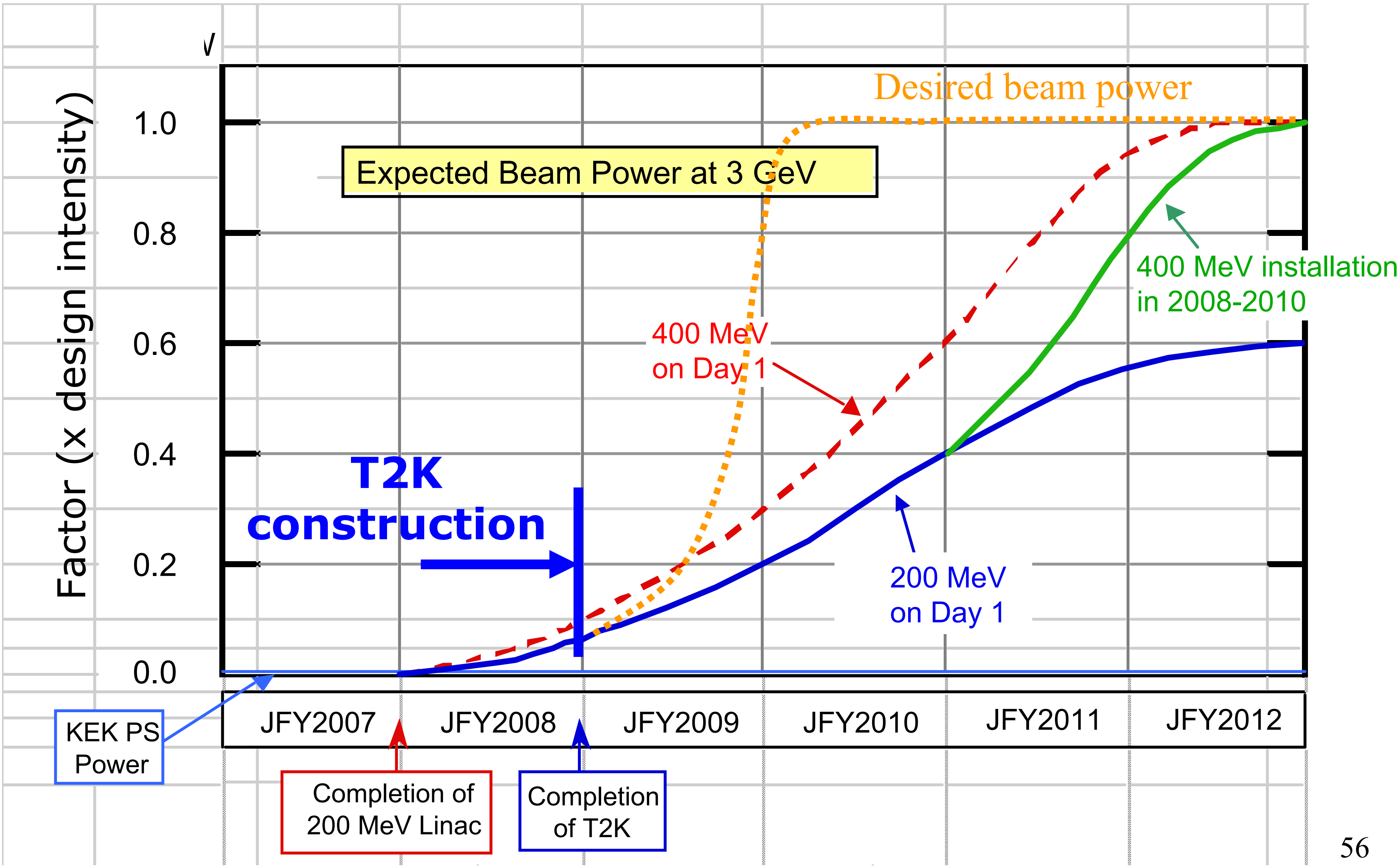
	Contingency	Total Cost M$
Far Detector		
Active detector	30%	80
Electronics and DAQ	55%	13
Shipping	21%	7
Installation	43%	14
Near Detector	44%	3
Building and outfitting	58%	29
Project management	25%	5
Additional contingency		14
Total	50%	165

J. Nelson

T2K power curve

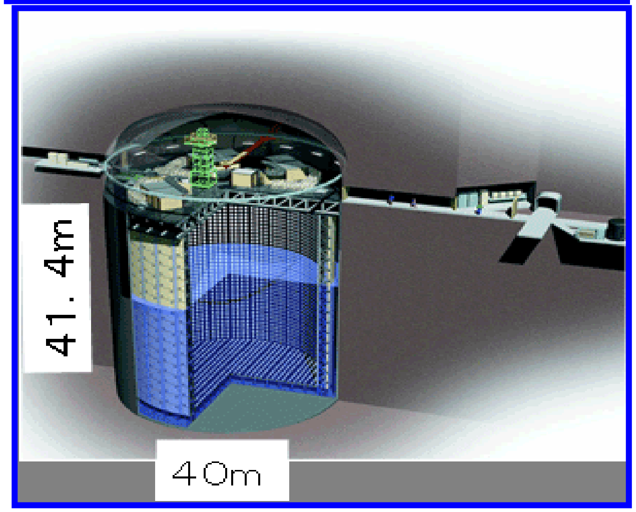


T2K Expected Beam Power



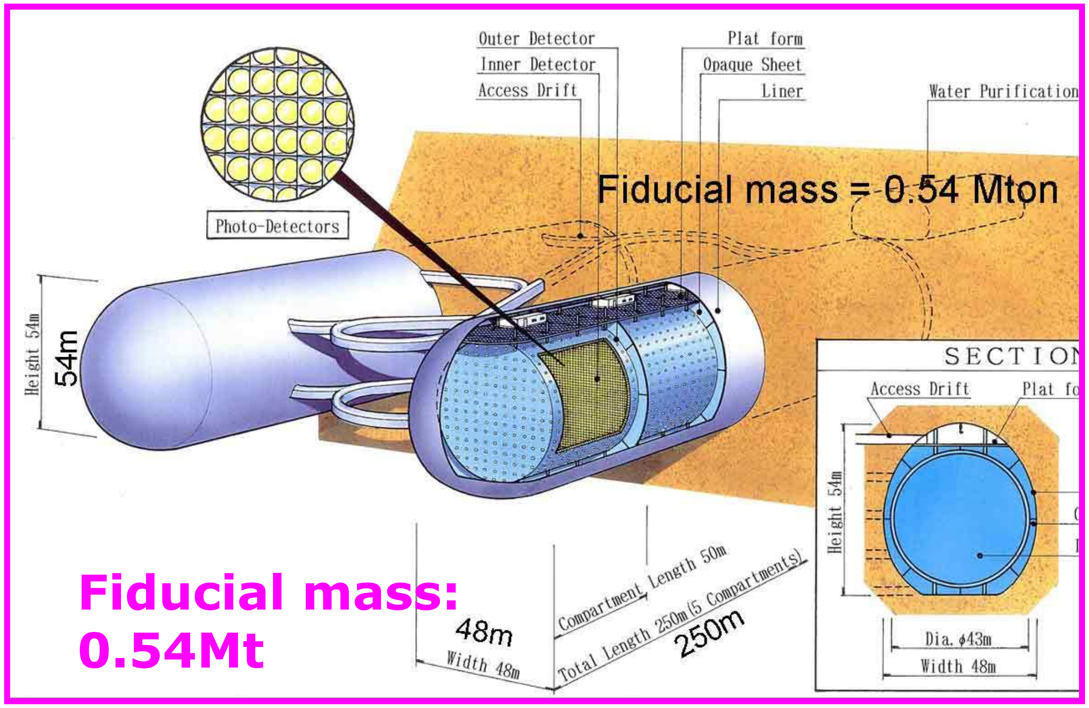
Hyper-Kamiokande

Super-Kamiokande
(50kt, 11000 PMT's)



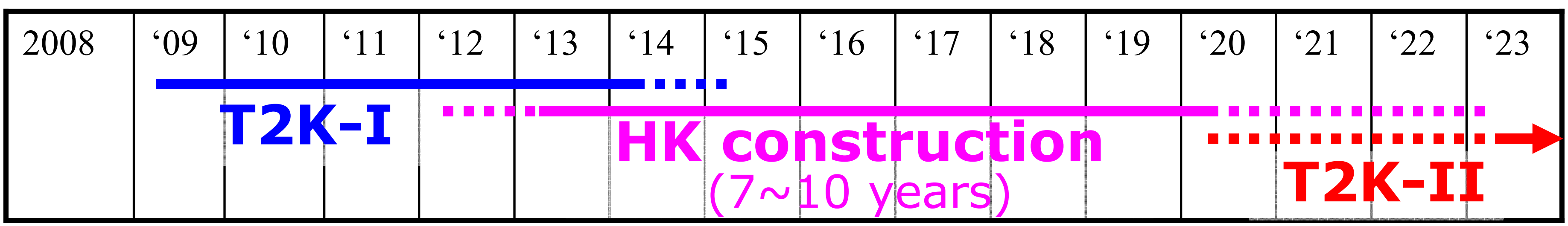
Fiducial mass: 22.5kt

Hyper-Kamiokande
(~1Mt, ~ 200000 photo-sensors)



Fiducial mass:
0.54Mt

- **Not official, Not approved**



Possible future reactor θ_{13} experiments

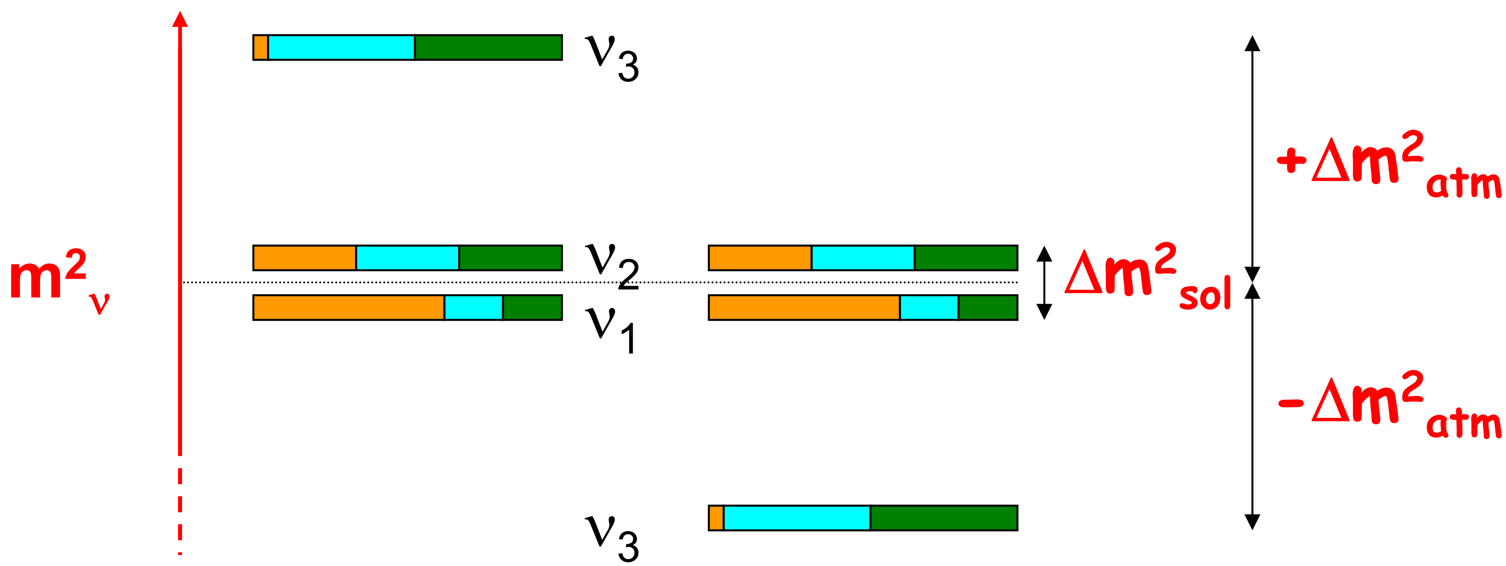
General characteristics:

- 2 (or more) detectors: 1 near (< ~0.5 km), 1 far (~1-2 km)
- Liquid scintillator (detection by inverse β decay)
- Overhead shielding required
- Goal is ~1% uncertainty
- Can be adapted for a $\sin^2\theta_W$ measurement, or an improved θ_{12} measurement

Experiment	Where	Baseline (km)		Overburden (m.w.e.)		Detector size (t)		$\sin^2(2\theta_{13})$ Sensitivity (90% C.L.)
		Near	Far	Near	Far	Near	Far	
Angra dos Reis	Brazil	0.3	1.5	200	1700	50	500	< ~0.01
Braidwood	US	0.27	1.51	450	450	65x2	65x2	<~0.01
Double Chooz	France	0.2	1.05	50	300	10	10	< ~0.03
Daya Bay	China	0.3	1.8-2.2	300	1100	50	100	< ~0.01
Diablo Canyon	US	0.4	1.7	150	750	50	100	< ~0.01
KASKA	Japan	0.4	1.8	100	500	8	8	< ~0.02
Kr2Det (Krasnoyarsk)	Russia	0.1	1.0	600	600	50	50	< ~0.03

Our knowledge

(flavors = e μ τ)



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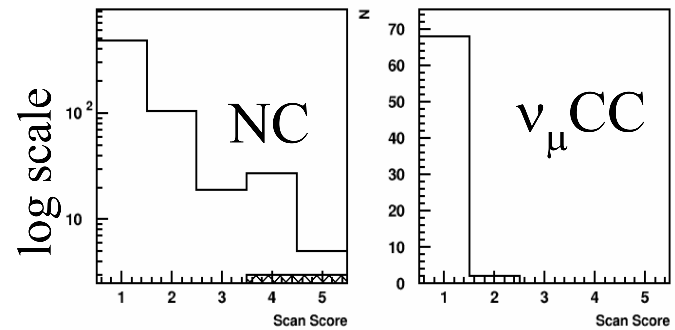
Training samples:
50 events each of ν_eCC, ν_μCC and NC
- individual samples to train
- mixed samples to test training



Blind scan of 450 events scored from 1-5 with
- signal=5
- background=1

open region: students
hatched region: + experts